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Ralph M. Parsons Co, Pasadena, Calif

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by

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

The subject of this report is an evaluation of various systems for converting solid wastes to energy. The information contained herein will be of interest to those involved in waste-to-fuel research and development programs, and to those involved in the purchase, design, construction, or operation of such systems. Inquiries and comments regarding the report should be directed to the Fuels Technology Branch of the Energy Systems Environmental Control Division.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

Waste quantities and characteristics in the U. S. are reviewed and waste-to-energy conversion technology evaluated. All waste materials, exclusive of those from mining operations, are considered. The technology is reviewed under the categories of mechanical processing, biological conversion systems, thermal/chemical systems, and combustion. Important features of many operating facilities are described and detailed engineering and economic analyses of seven specific systems are presented. An analysis is also made of the technology and costs for conversion of pyrolytic off-gas to methane, methanol, and ammonia. Environmental pollution data are presented where available and the current control technology briefly reviewed. Conclusions on the conversion technology are made and research needs considered in a series of recommendations.

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SECTION 1

INTRODUCTION AND SUMMARY

The solid waste generated in just the larger metropolitan areas of the country could, if converted to energy, supply up to one percent of the nation's total energy needs. If available agricultural wastes could also be converted into usable energy, the percentage contribution would be closer to 6%. During the past ten years there have been developed several approaches for converting wastes into fuel or directly into energy. Recognizing that there existed much relevant information and many competing technologies for waste conversion, the EPA in 1975 initiated a project to evaluate the use of solid waste as a means of supplementing conventional energy sources. The results of that project are the subject of this report. The purposes of the project were to:

- Determine the best estimates available concerning the quantities and characteristics of waste materials, exclusive of mining wastes, in the United States.
- Survey existing and proposed waste-to-energy technologies, and identify the ones of most current interest to potential system users.
- Carry out in-depth engineering and economic analyses on selected systems.
- Recommend research and development needs in the field of waste to energy systems.

WASTES AVAILABLE FOR ENERGY CONVERSION

Although considerable variation exists between various estimates of available combustible wastes, there undoubtedly exists an impressive amount of waste. The most reliable estimates, given in terms of available (recoverable) dry combustibles, are shown on the next page.

	Year					
	Early 70's		1980		1990	
Waste Stream	Tg	10^6 Ton	Tg	10^6 Ton	Tg	10^6 Ton
Municipal						
Municipal Solid Waste	61.1	67.4	78.0	86.0	98.0	108.0
Sewage Sludge	11.5	12.7	14.0	15.4	16.5	18.2
Industrial	42.3	46.6	48.2	53.1	49.9	55.0
Agricultural	201.2	231.7	316.2	348.5	384.6	424.0
TOTAL	325.1	358.4	456.3	503.0	549.0	605.2

On the assumption that the dry and combustible fraction of most wastes has a higher heating value (HHV) of 18.61 MJ/kg (8,000 Btu/lb), the total energy value of U.S. wastes will increase from the 6049 PJ (5.734 x 10^{15} Btu) of the early 70's to an estimated 10 214 PJ (9.682 x 10^{15} Btu) in 1990. In terms of oil equivalence, this amounts to 910,200,000 to 1,537,000,000 barrels.

TECHNICAL PROCESSES

There are many systems for converting wastes into energy either in operation commercially, or under some stage of development. Combustion processes are available for converting wastes directly into heat energy. Other systems involving various thermo-chemical, mechanical, and biological processes are either available or under development to convert wastes into more usable liquid, gaseous, or solid forms of fuel. In most cases surveyed it was found that the technology in question, rather than being new, was usually just new to the waste conversion field. Of the systems surveyed, the following were selected for in-depth engineering and economic analysis. These systems are:

RESCO-Saugus Combustion System

Hamilton, Ontario, Waterwall Incinerator

Nashville Thermal Transfer Corporation

City of Chicago-Commonwealth Edison Supplementary Fuel Plant

Georgia Institute of Technology Mobile Agricultural Pyrolysis System

ANDCO-Torrax Air Blown Pyrolysis System

Union Carbide Corporation Oxygen Blown Pyrolysis System

Occidental Research Corporation Flash Pyrolysis System

The results of the in-depth analyses are contained in the body of the report as Sections 3 through 9. The results of the broader technology and waste surveys, along with support information, are in the Appendices. Primary units in this report will be noted to be in the modernized metric system known as SI. An explanation of these measurement units is also given in the Appendix.

In that the decision to select one system over another is so extremely site specific, depending upon such factors as local demand for the energy product and characteristics of the particular waste being processed, no attempt was made to rank the systems on a comparative basis. Much of the information in this report could certainly be useful in developing such a comparison. However, to make such a comparison meaningful, the information contained in this report should be modified by local and regional considerations.

CONCLUSIONS

Conclusions relating to the individual systems studied are in that part of the report dealing with the subject system. More general conclusions are contained in Section 11. Major conclusions of the projects were:

- To date there has been very little data published on environmental emissions and effects from conversion plants. Past and on-going test results should be immediately documented and issued to those concerned. Applicable regulations and a brief review of the best available control technology should be included.
- Much developmental work is still needed to establish the best types of equipment for handling and processing solid wastes. Most of the existing systems have been adapted from non-solid waste usage.
- The physical and chemical characteristics of the various types of refuse-derived fuel are still largely unknown. There is need for the characterization of these fuels, and for the characterization of various blends of these fuels with fossil fuels.
- More R&D work is needed to develop fundamental information on pyrolysis chemistry and applied studies are needed to advance the state of the art.
- There is little information available on the combustion characteristics of refuse-derived fuel. The body of the report contains several specific suggestions for increasing the amount of knowledge in this area.
- A number of facilities in operation or undergoing start-up tests can convert wastes to energy in a manner economically attractive to both the waste generator and the energy purchaser.

As the cost increases for producing energy and for disposing of wastes, waste-to-energy systems will become even more economically desirable. The results of this project indicate that although there are problems yet to be solved, they are certainly not insurmountable. The information provided in this report will add to the needed solutions and advance the day when solid wastes can contribute their energy content to the nation's fuel needs.

SECTION 2

METHODOLOGY

INTRODUCTION

Economic, technological, environmental, and public acceptability factors all influence the eventual success or failure of a commercial scale waste-to-energy processing facility. The actual sensitivity of each factor in influencing the total system, however, cannot be predicted on considerations of national averages and any listing of systems in some form of ranking by value is essentially meaningless.

Planning must nevertheless begin with some more or less uniform guidelines, basic assumptions, and data base. The availability of this fundamental information to local government and industrial organizations therefore serves a useful purpose in the overall process of reaching a decision on incorporation of a processing plant into waste management plans. While the general survey results presented here will assist in understanding the overall field of concern, examples of specific detailed analyses are necessary to indicate the methodology to be followed in conducting the local studies. In that it was logical to select the systems to be so analyzed after review of all potential systems, no definite number or type of facilities were specified within the formal contract work statement. The selection process that was used for the actual systems discussed within Sections 3 through 9 is reviewed here along with the other methodology applied.

STATUS OF TECHNOLOGY

A review of any technology reveals a similar grouping of individual projects into such categories as:

- Conceptual processes based on theoretical considerations, fundamental scientific information, or observations of analogous reactions or techniques within other technologies.
- Full-scale plants under construction, or completed and start-up testing still in progress.
- Fully "mature" production plants: the mere fact that a facility has been in operation for a number of years need not imply that it was properly designed and that many problems are not being experienced.

Processes for converting wastes to energy forms are to be found in each of the above categories. In terms of absolute number of reports, the great majority were found to fall towards the top of the category listing. Such basic work is of course essential to eventual commercialization of a new system some 8 to 10 years after the initial laboratory experiments. Its use for any analysis other than the most tentative can lead to erroneous conclusions, practically always on the optimistic side. Homogeneous, finely divided, and oftentimes synthetic samples of waste are used under energy-input conditions that bear no relationship to techniques to be used in production. No information is derived on the practical--and costly--problems of materials handling and environmental controls. The process developer for the early stage work, typically not knowledgeable in modern construction methods and their costs, can associate with his process highly favorable economics that will not be at all truly assessed until undue effort has been expended. Much of the current small scale research is of high caliber and covers the full range of technology possibilities, but by its very nature such work does not lend itself to quantitative process analysis.

The extent of information available on systems beyond the bench-scale level is a function of the complexity of the overall process and the funding the developer could allocate to or solicit for the project. This support, prior to the demonstration plant final design, can be as high as $10 million, and hence few systems progress to this stage. Processes within these larger scale capacities are in general well researched. The data available are characterized, however, by the necessarily limited objectives of the developer, rather wide deviations under supposedly fixed conditions, and the lack of some essential measurement (oftentimes as fundamental as the input waste composition). These limitations of course affect the accuracy of any further engineering analyses in that theory is not sufficiently advanced to estimate the effect of process variables or the value to be assigned to missing data points.

CRITERIA FOR CANDIDATE SELECTION

Review of the pertinent information sources indicated the following criteria should be used for developing a total listing of potential candidate systems and for further narrowing down this group to a number suitable for a report meeting the objectives of the contract:

- The final listing should encompass several types of processing technology, preferably at least one from each of the fields of mechanical processing, biological conversion, thermal/chemical conversion, and combustion.

- The systems should be capable of processing a variety of input waste materials.

- A variety of output energy forms should be shown as examples.

- The stage of development should be such that process information is sufficiently reliable to yield estimated construction costs for full scale plants accurate to on the order of ±25%.

- A recent detailed engineering analysis is not available.
- While all systems should be of advanced design, a range of level of development should be included within the listing of candidates.

An original listing of 13 systems was prepared, meeting most of the above requirements, as follows:

- The Pompano Beach, Florida, anaerobic digestion system
- Landgard, Baltimore, pyrolysis system
- Ames, Iowa, RDF plant
- Milwaukee Americology RDF plant
- Sanitary landfill methane recovery
- Wet processing RDF (Black-Clawson)
- The RESCO and Hamilton Combustion Systems
- Nashville Thermal Transfer Corporation
- City of Chicago Supplementary Fuel Plant
- Georgia Tech Mobile Pyrolysis System
- ANDCO-Torrax Air Blown Pyrolysis System
- Union Carbide Purox Pyrolysis System
- Occidental Research Corporation Flash Pyrolysis System

This quantity was considered to be an excessive number and would have resulted in a report of such length that reader interest would have been lost. The initial six were eliminated and comments on two of these are deserved. Biological conversion systems are considered to offer significant technical advantages when the raw wastes have a high water content, yet an example is not present in the final listing. This results from the fact that the Pompano Beach anaerobic digestion system is not yet operational and the experimental results from methane generation at this level of processing are essential to any engineering/economic analysis beyond the several detailed reviews of laboratory scale work now available. The Monsanto Landgard pyrolysis system at Baltimore is the largest pyrolysis system in the U.S. It is not contained within the candidates because at the time of the preparation of this report the facility was undergoing modifications to solve mechanical problems and to reduce atmospheric emissions. The process yields a hot, low heating value, gas that is immediately combusted to raise steam, and an example of a pyrolytic steam generator is given in the form of the Andco-Torrax system. In addition, the Landgard plant has been described adequately in a number of publications.

Contained within the engineering analyses are two rather detailed discussions of typical equipment and building requirements of processing facilities. These details are cited for a refuse-derived supplementary fuel plant (City of Chicago) and for a pyrolytic system yielding a medium-heating value gas (the Union Carbide PUROX system). In an extension of this latter section, Appendix C contains a discussion of the conversion of a pyrolytic syngas to other products. Attention is directed to the fact that the PUROX equipment as now offered for sale by UCC only is intended to produce syngas and the additional analysis is wholly that of The Ralph M. Parsons Company.

INFORMATION SOURCES AND BACKGROUND NEEDS

Information was obtained through (1) letter and telephonic requests to known investigators; (2) computer-generated retrieval listings of the EPA and the Smithsonian Science Information Exchange; (3) conference proceedings of the last 8 years; (4) continuing review of trade journals and newsletters; and (5) field visits to government, university, and industrial authorities. Each of these primary sources led to a number of other sources, which in turn generated additional documents or contacts. A logging, abstracting, follow-up, storage, and retrieval system was organized for administration of the information system. Reports were reviewed by specialists in process chemistry, equipment design, materials handling, biology, economics/cost estimating, and environmental controls.

In preparing the engineering analyses of the candidate systems, close cooperation with the facility developer or operator was essential. A number of the systems have not yet reached a stage of commercial-scale processing capacity and hence it was necessary to establish probable total plant needs according to current construction practices and applicable codes and regulations. This was typically accomplished in a series of steps, beginning with a request to the owner/operator to supply experimental process mass and energy balance data, the concept for a plant lay-out for his recommended processing capacity, and an initial cost estimate for equipment. The project staff at Parsons then reviewed this information, added necessary interface and accessory equipment design, and prepared an independent cost estimate based on actual construction experience and factors utilized within the Architect-Engineering profession.

The cost elements were derived from vendor discussions and quotations; trade journal indices for current costs of materials, equipment, and labor; and values obtained from on-going construction projects within the four operating Divisions of Parsons. While only energy products were of immediate concern here, certain of the processing steps yield both fuel and isolated material commodities from the waste. No attempt was made to allocate costs between these two functions. Estimates presented indicate all sub-systems involved in a given facility, and these should be carefully reviewed before conclusions are sought on relative costs. Those plants yielding a material product can of course gain income from sales of those materials. Such credits can have important off-setting effects on capital recovery and operating expense costs. Because the subject of total plant economics is one where condensation of information can lead to misinterpretation, no attempt has been made to give a summary of this area.

Process modifications on the preliminary systems were suggested by Parsons and comments upon these solicited. After agreement had been reached on a rather detailed design, capital and operating costs for the facility were developed with greater accuracy and scaling factors established where applicable to ascertain cost-capacity sensitivities. The developer then reviewed the final version of the analysis as given in this report. The candidate systems contain either some items of a proprietary nature or equipment not yet verified as to its effectiveness at commercial processing capacity, and hence some uncertainty exists within the estimates. It is nevertheless believed that the costs presented herein are the most accurate yet published.

Organizations considering the possible financing and construction of a full-scale waste processing facility must have available to them a staff of specialists knowledgeable in a wide variety of fields. Administrative officials or executives need not possess the detailed expertise of the planning and engineering personnel, yet they should appreciate certain of the principles upon which decisions will ultimately be based. Review of all of these speciality areas is outside the scope of this report and only one of them, environmental pollution abatement, is discussed here. This is done within Appendix D in that the review of this subject matter is not essential to the understanding of the processes themselves. Within each of the discussions of the individual candidate systems is presented the best available information on effluents from the processes.

Economic evaluation is the other area that decision makers must understand at least in general terms. The estimation of true long term net costs (or profits) is a difficult task that must be approached realistically. All possible expenditures attributable to the waste processing facility must be established and revenues should be considered only after adequate market surveys have been completed. Numerous texts on capital investment theory are available and these should be consulted prior to approval of project funding.

SECTION 3

THE MASS BURNING COMBUSTION SYSTEMS OF RESCO-SAUGUS AND HAMILTON, ONTARIO

Both of these facilities are rather large waterwall combustion systems, each having its own unique design features, and they are considered together here as a single candidate type.

REFUSE ENERGY SYSTEM COMPANY (RESCO), SAUGUS, MASSACHUSETTS

Introduction and Summary

This private corporation, a joint venture of Wheelabrator-Frye, Inc., and M. DeMatteo Construction Company, owns and operates a mass burning, water walled combustion system normally handling 1090 Mg/d (1,200 TPD) of solid waste with an output of 3810 Mg/d (8.4 million lb/day) of steam for industrial use. This system was designed by Wheelabrator-Frye, the exclusive licensee in the United States and Mexico for the Von Roll technology. The steam produced is sold to the General Electric Company Lynn Works, directly across the river from the plant.

Proven technology is used throughout the facility and a high degree of reliability is incorporated into the design. A thorough waste supply and product sales analysis was made prior to construction of the plant, assuring that the facility was adequately funded and could profitably serve both the local area and the owners.

Conclusions

The Saugus plant of RESCO serves as an excellent example of how waste materials can be technically and economically converted to energy. Because the RESCO combustion system is privately owned, not all the details of its operation are available. Nevertheless, the plans and procedures of this facility typify elements important to the success of such a plant.

- Waterwall combustion systems for refuse are the best established of all waste-to-energy processes. It is recommended that governmental and industrial organizations who have narrowed their conversion options to inclusion of such processes thoroughly review the relative advantages of the RESCO facility.

- A thorough and realistic analysis must be made of the quantities and characteristics of wastes available for energy recovery. Committments must be obtained for sufficient quantity of waste over the useful plant life, with financial arrangements mutually beneficial to buyer and seller. RESCO accomplished this with the communities within a reasonable distance of the plant.

- Because energy is a product subject to all normal economic forces, purchases must be assured prior to expenditure of large amounts of capital. The arrangement made by RESCO for sales of steam to General Electric, in addition to contractual agreements on joint utility and supply needs, assured a sound revenue base that assured raising of necessary funds.

- Design was accomplished by a highly qualified engineering organization with the freedom to specify equipment and subsystems with high-performance standards. No attempt was made to either "cut corners" or to incorporate technological advances not yet proven.

- Start up testing was approached realistically anticipating problems typical to any new facility. Funds were immediately available to make any necessary modifications and corrections.

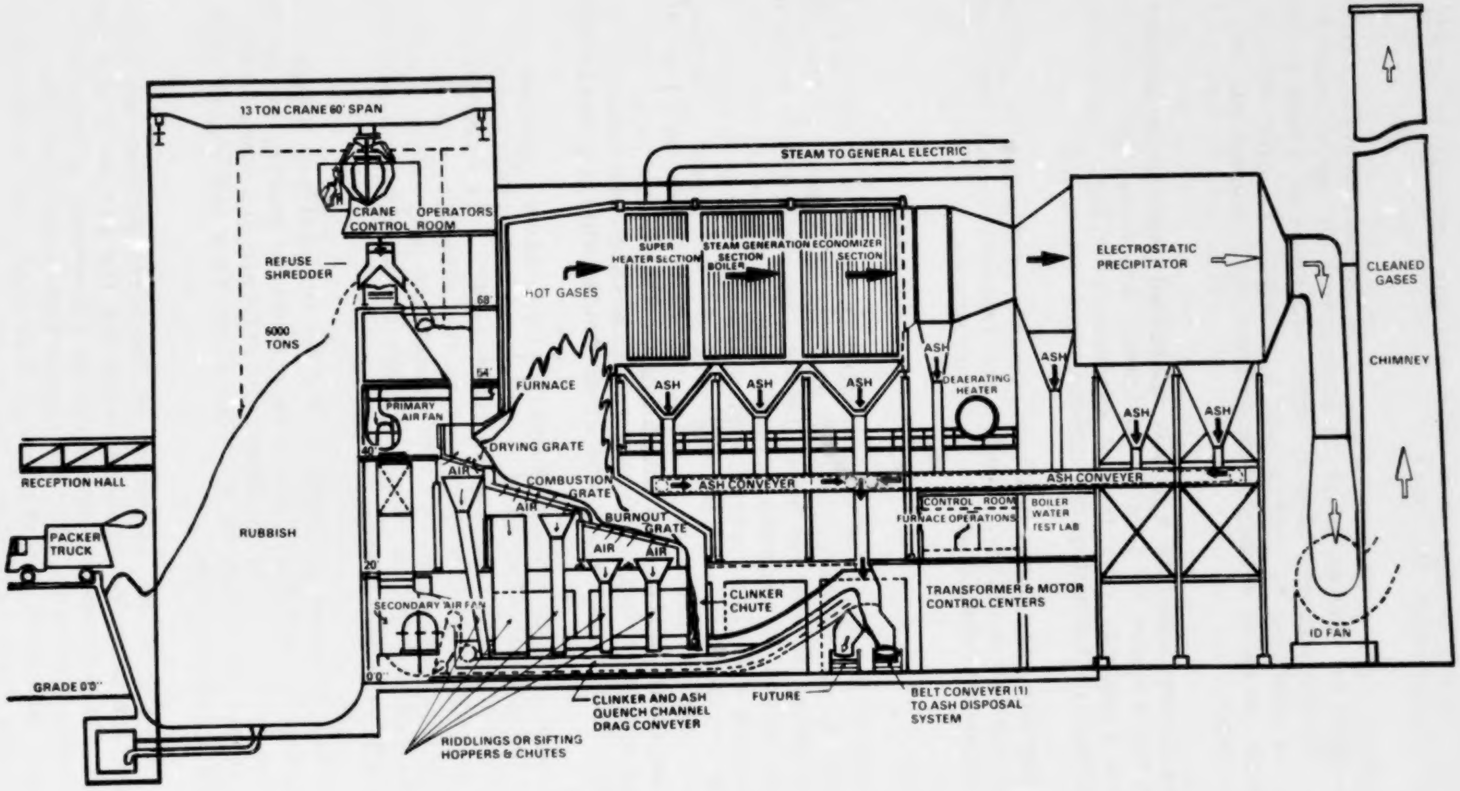
Process Description

A cross section of the facility is presented in Figure 1. Processing begins with the arrival of refuse collection or transfer trucks at the plant. As in most waste disposal facilities built in the last decade, all loaded trucks pass over an automatic recording truck scale to determine and record load weight for billing and plant operational planning. After weighing, the trucks dump the raw refuse into a large receiving pit and depart. Refuse remains in the receiving pit until it is moved by the bridge crane and clamshell grapple to the steam boiler charging hopper. The bridge crane and grapple is manually operated from a control cab from which the operator has a direct view of all refuse receiving, and steam boiler charging operations.

A shredder is used only to reduce unusually large items. Refuse is fed to it by the crane and grapple when in the judgment of the operator the refuse pieces are too large for charging to the boiler. This bulky waste is loaded on to a shredder feed conveyor, fed to the shredder, and the shredded material returned via a chute to the receiving pit. Only a small portion of the total refuse handled passes through the shredder, a practice quite typical of European operations.

Refuse as received is moved directly to the boiler charging hopper without any pre-processing, and this hopper then feeds by gravity on to the drying section of the grate. It is necessary to maintain the hopper well filled with refuse to act as a plug to keep the flame from the boiler from blowing back out the hopper opening.

Refuse fed into the boiler is burned on the three-section Von Roll grate. The first section provides space and time for the refuse to dry out prior to combustion. Primary combustion occurs on the second section and final burnout on the third section. The hot gases from combustion pass through a superheating tube bank, an evaporator tube bank, and an economizer tube bank before exiting from the boiler. The steam, produced at 4.86 MPa


13 TON CRANE 60' SPAN
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OPERATORS ROOM
REFUSE SHREDDER
6000 TONS
RUBBISH
RECEPTION HALL
PACKER TRUCK
GRADE 0'0"
68'
54'
40'
20'
0'0"
PRIMARY AIR FAN
SECONDARY AIR FAN
AIR
AIR
AIR
AIR
FURNACE
HOT GASES
DRYING GRATE
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FUTURE
BELT CONVEYER (1) TO ASH DISPOSAL SYSTEM
RIDDLINGS OR SIFTING HOPPERS & CHUTES

Figure 1. Typical cross section of Resco facility.

(690 psig) and 468°C (875°F) is piped to the General Electric Co., Lynn Works, 914m (3000 ft.) away.

The flue gas passes from the boiler through a Wheelabrator-Frye electrostatic precipitator to the stack. Auxiliary equipment such as forced draft fans, pumps, etc., are not shown as part of the process flow diagram.

Bottom ash from the end of the burnout grate and siftings that pass through the grates are collected in a quench tank. This tank is equipped with a drag chain conveyor to move the cooled wet ash to a metal and aggregate recovery system. Fly ash from the several boiler tube tanks and the precipitator is collected by an ash conveyor that discharges the fly ash through a chute to combine it with the bottom ash as it is conveyed to a material recovery system.

The material recovery system consists of several ash handling conveyors and a rotating screen. The large metal pieces making up most of the coarse material from the rotating screen are conveyed to a metal holding bin where they are sold to metal salvage firms. The fine screenings are magnetically scalped to reclaim small pieces of ferrous metal, which are sold. The fine ash is conveyed to trucks for disposal in a landfill.

In addition to the refuse-to-steam process described above, there are some related activities that are not in the direct process flow, but nevertheless contribute to a successful operation. These are:

- Auxiliary fuel firing - In order to meet the requirement of maximum reliability in steam supply demanded by the steam customer, provision is made for two back-up steam systems. First, each refuse boiler is equipped to burn oil in order to ensure the availability of steam if refuse is in short supply and to provide a peaking steam capacity. Second, two standby oil-fired water tube boilers are provided which have a total steaming capacity approximately equal to the average demand on the plant. Usage of these systems will be dependent on the uniformity of supply of refuse and demand for steam.

- Feedwater - The steam supply contract with General Electric Company includes a requirement for feedwater return as needed, preheated to 121°C (250°F). This does not eliminate a need for water make-up but it does reduce the amount needed and simplifies water treatment.

- Oil supply - The steam supply contract also requires that General Electric provide the auxiliary fuel oil via pipeline. This eliminates a requirement for tankage at the steam plant and shifts the burden of ensuring oil availability to the steam customer.

- Electric power - G.E. has electric power generating capacity for 80,000 kW, including 20,000 kW of gas turbine generator capacity not dependent on a steam supply. In addition, G.E. has a 20,000 kW tie with the Massachusetts Electric Company. These units are able to supply the 6510 kW connected load of the steam plant. Payment to

G.E. for both power and the fuel oil used will be made by supplying an equivalent additional amount of steam.

Equipment Details

The foregoing process description gives a brief discussion of the flow of materials through the facility. This section contains a more detailed description of the major equipment items and an explanation of their operating characteristics as related to the process.

Scales--

The automatic recording truck scales are activated by a coded plastic card carried on each truck authorized to dump refuse at the facility. This card identifies the truck and its owner, for billing and input of correct empty truck weight. The empty weight of each truck is recorded in the scale system, making it unnecessary to exit over the scales every time a load is delivered. Periodic empty weight checks are made to keep the record current.

Receiving Pit--

The refuse receiving pit is a 26 m (85 ft) deep by 61 m (200 ft) long by 12 m (39 ft) wide concrete pit that the designers calculate to hold 6078 Mg (6700 tons) of refuse when filled to maximum capacity, equivalent to 5.6 days of steam generator operation. The normal capacity is 2540 Mg (2800 tons), enough for 2.3 days of operation. The high level of maximum capacity serves two purposes. It provides storage capacity to cover an unusual or unforseen situation and it permits future expansion of the facility without increasing the size of the pit, an expensive undertaking.

Travelling Cranes--

There are two overhead bridge cranes on a common runway over the receiving pit. Each is equipped with a 2.7 Mg (3-ton) refuse grapple and is controlled by an operator riding with the crane in an air conditioned cab. There is provision for adding one more crane when the plant is expanded. These cranes feed the refuse to the boiler charging hoppers or to the shredder feed conveyor as necessary and in addition do some mixing of refuse in the pit. Both cranes can serve either of the two boilers.

Shredder--

There is a single 22.7 Mg/h (25 TPH) hammermill that is used to reduce occasional oversized waste to 30 cm (12 in.) or less size. Agreements with the cities that deliver their waste to this facility prohibit the dumping of dangerous materials or those that are excessively large or extremely heavy. Nevertheless, some items received must be reduced in size in order to be acceptable for burning. The shredded material is returned to the pit.

Boiler Charging Hopper--

The system of charging refuse to the steam generator furnace in the RESCO design is a simple gravity chute or hopper that depends on the weight of the refuse in the hopper to move the refuse out the bottom and on to the furnace grate. The hopper must be long enough to provide a sufficient plug of refuse to retain hot gases in the furnace. The hoppers in this facility are equipped with nuclear bin level indicators that will sound an alarm to warn the crane operators when the bin level is low and there is potentially an insufficient plug to retain the hot furnace gases. A portion of the hopper nearest the furnace opening is water cooled by some of the boiler make-up water.

Steam Generators--

The two steam generators are each rated to burn a maximum of 680 Mg (750 tons) of municipal solid waste per day while producing steam at 4.86 MPa (690 psig) and 486°C (875°F). Normal operation is 544 Mg (600 tons) per day per unit and the overall plant operation is planned for this average amount. At this throughput, average steam output will be 79.4 Mg (175,000 lb) per hour per unit, assuming an average waste heat content of 10.47 MJ/kg (4,500 Btu per lb).

The steam generators are Von Roll design waterwall boilers with three level inclined reciprocating grates. The reciprocating grate action both moves the refuse down the incline and turns it to ensure complete combustion. Final burnout occurs on the last grate section and the ash is then discharged into a water sealed hopper for quenching and removal.

Primary combustion air is introduced beneath the furnace grates. The intake for the primary air is in the refuse pit area, which causes this area to be constantly under a slightly negative pressure with all air flow inward and toward the fan. By this simple arrangement, any odors are reported to be retained in the pit area and ultimately burned away in the boiler.

Secondary air is introduced above the grates through nozzles in the refractory walls. The water walls of the boiler start at a level above the grates. The furnace is refractory lined at the lower level near the grate where there is the possibility of a reducing atmosphere. The overfire secondary air is used to help complete combustion and keep the flue gas temperature within working limits. The gas temperature must be maintained between 871°C (1600°F) and 1093°C (2000°F) to obtain proper boiler performance and to inhibit corrosion of the water tubes of the steam superheater, generator, and economizer.

The superheater, generator, and economizer are constructed in the form of vertically-hung tube panels. This design allows the use of mechanical rappers to clean ash and scale off the tubes.

Standby Boilers--

Two oil-fired, package type water tube boilers are provided for standby steam production when the main refuse burning boilers are out of service for any reason and to serve also as peaking units, supplying additional steam during peak demand periods. These boilers are each rated at 54.4 Mg (120,000 pounds) of steam per hour at a design pressure of 4.86 MPa (690 psig) and a temperature of 454°C (850°F). They share major auxiliaries such as feed water treatment and fuel supply with the main boilers.

Air Pollution Control--

Each refuse boiler is equipped with a Wheelabrator-Lurgi electrostatic precipitator for removal of particulate matter from the flue gases. These are two-field type units sized for a boiler discharge of 5660 m^3/min

(200,000 CFM) of flue gas at a temperature of 220°C (428°F) with a particulate loading of 2.4 to 4.8 g/m^3 (1 to 2 $grain/ft^3$) adjusted to 12 percent CO_2. They are designed for a collection efficiency of 97.5 percent to maintain emissions to the atmosphere within the allowable 1.77 g/m^3 (0.05 $grain/ft^3$). The design specific collection area (SCA) is 19.42 m^2 (209 ft^2) per 28.3 m^3 (1000 ft^3) of flue gas.

There is no equipment specifically dedicated to control of oxides of nitrogen. Instead, production of NO_x is curtailed by holding boiler temperature below that required for significant formation of NO_x from atmospheric nitrogen. Further, the relatively low heat content of refuse and the handling of the fuel during combustion precludes the generation of localized high heat zones and high flame temperatures. Refuse is a low nitrogen fuel and would contribute little to the production of NO_x from, that source. It should be noted that the air quality standards of the Commonwealth of Massachusetts specifically permit the use of process control to meet emission requirements, as discussed above, in lieu of special emission control equipment, provided that measurement verifies emissions are below the permitted maximum levels.

Refuse is a low sulfur fuel with a sulfur content of less than 0.3 percent and normally less than 0.1 percent. Such a low sulfur content in the fuel will maintain sulfur dioxide emissions below the permitted maximum levels without any added controls or equipment. The auxiliary fuel oil used also has an equivalent low sulfur content.

Ash Handling--

The bottom ash and siftings from the grates drop through collection hoppers to a quench tank below each furnace. Ash is removed from the tank by a drag chain conveyor and delivered to an ash disposal system. This method of handling ash is quite common where an ash-producing fuel is used. It is simple, easily operated without sophisticated controls, and is quite dependable.

Fly ash is collected from the precipitator and boiler hoppers by a long enclosed conveyor and dropped through a chute to the ash quench tank for further processing with the bottom ash. It is a simple system that is facilitated by the in-line and comparatively level arrangement of the various hoppers so that they can be readily served by one long conveyor. There is provision to by-pass the quench tank if a market for the fly ash is developed.

The wet ash removed from the quench tank is transported by conveyor to a material recovery building where salvageable metals are separated from the ash and facilities are provided to load metals and aggregate on to waiting trucks for sale. The entering ash is screened in a rotating trommel to separate bulky metals from the fine metal and aggregate materials. The fine screenings are scalped by a magnetic separator to remove fine ferrous metals. Separate storage hoppers are provided for the large metal screenings, fine ferrous metal, and aggregate material.

Water Use--

The in-plant water use and distribution system is designed to maintain usage and waste water disposal quantities to a minimum. The average water consumption, mostly to produce steam, is 0.027 m^3/s (430 gpm). The average discharge of waste water is only 0.0008 m^3/s (12 gpm), of which 8 percent is estimated to be sanitary waste. In order to arrive at this low figure of total water waste, some prudent design features were incorporated to make multiple use of water where possible. For example, a portion of the boiler make-up water is used as cooling water on the boiler feed chutes and ash discharge part of the waste stream. Another lesser example is that the pump gland seal water and other miscellaneous waste water streams are drained to the ash quench tank to form part of its make-up water. The waste water is pumped to the City of Saugus sewer system.

Existing Operation

This facility started up in late 1975 and there has not been enough operating experience with it to develop reliable data on its operation. RESCO, the owners and operators, have stated that the plant is meeting the design objectives and that initial actual operating and maintenance costs are within the expected range.

Engineering Evaluation

This facility must be considered as one utilizing a very conservative engineering approach for the conversion of refuse to useful energy. Its European mass burning technology has been developed and proven in service in many installations for years and the key items of equipment, the furnace and the grates, are of European design. With the adoption of a well developed waste-to-energy system, the inherent problems of the associated equipment are known and can be guarded against by careful design. For example, the tendency of a mass burning furnace to have a corrosive reducing atmosphere immediately above the fire is well known. The designers of this facility have guarded against this condition by lining the lower section of the furnace with refractory material and by careful control of combustion air. Any fireside tube wastage noted can be controlled through proper adjustment.

This facility represents the latest and most recent advance in the existing mass burning technology. It is larger than any previous similar installation and the operating steam-pressure and temperature, at 4.86 MPa/468°C (600 psig/875°F), are slightly higher than normally used in most water walled systems.

Precipitators--

Stack emission tests have been performed by both the Federal EPA and the Massachusetts Bureau of Air Quality Control. In both cases the particulate emissions were within the established legal limits, which indicates that the boiler emissions are in the expected range and that the precipitators are functioning as designed. Total solid particulates measured have been in the range of 0.106 to 0.131 g/Nm^3 (0.044 to 0.054 grains/SCF) corrected to 12%

CO_2. The average value in the official EPA Method 5 tests was 0.119 g/Nm^3 (0.049 grains/SCF).

Bridge Cranes--

The cranes have been variously quoted as having a 10.5 Mg (13 tons) and a 2.7 Mg (3 ton) capacity. Both figures are correct. The higher rating is the gross lift rating of the bridge and includes the weight of the grapple. The lower rating is the actual weight of refuse that could be lifted by this crane.

There has been some comment in the industry that there was severe wear of the bucket hoisting cables when this facility went into operation. If this is true, it is to be expected in a new installation where crane operators have not yet gained the experience needed to operate cranes rapidly yet smoothly. Further, cable life on cranes of this type is normally not very long, particularly on the bucket closing cable. Cable replacement every two months is not considered unusual.

Water Walled Systems--

The incinerator furnaces at Saugus are the mass-burning type, i.e., the refuse is burned on a grate in the same condition as received, without preprocessing. A comparison of the steam output conditions to the refuse input indicates a design thermal efficiency of 71.4 percent. Shredded refuse would have a higher volumetric heat release rate and a thermal efficiency somewhat greater than this. It is apparent that RESCO has chosen to sacrifice a few percentage points in efficiency in favor of using a well known and developed technology.

The choice of mass burning boiler normally require the recovery of metals to take place after combustion. RESCO does sell the ferrous fraction, but aluminum is not recovered, as the owners have established to their satisfaction that its recovery is not economically feasible at this time.

Reliability--

With the ability to fire oil as well as refuse in the main boilers and the existence of two oil-fired standby boilers, the reliability of steam supply to the customer is assured.

The facility has two waste burning boilers that will both be required in service to meet the normal average waste load. One can act as standby for the other in the event of an unscheduled outage. The boilers have been designed carefully and conservatively, using the best information available, so that unscheduled outages should be rare, but they can and probably will occur. With this facility in service, the existing landfill, which could be a back-up disposal facility, is closed. Short term outages of a few days are amply provided for by the huge capacity of the refuse receiving pit, which is capable of storing 5.6 days of refuse as it is received on the average.

The cranes serving the boilers gain reliability by being installed so that each can serve either furnace. If this should prove inadequate, there is provision for the future installation of a third crane.

Project Development

Although this refuse-to-energy project is based on technology previously used and even though there are as many as 54 similar previous installations, the Saugus facility is unique, just as every refuse-to-energy facility is unique. Most times the conditions that create the need for such facilities are different in every locality.

There are several basic conditions that nevertheless must be met by every entrepreneur, whether public or private, in order to establish a financially successful refuse-to-energy operation. Each of these basic conditions, and how RESCO met them, are discussed below.

Preliminary Financing--

In order to initiate any sizeable refuse-to-energy project, it is necessary to study the requirements, review the project feasibility, prepare preliminary designs, and spend a great deal of time in discussion and conferences with interested and involved parties. The initial impetus for this effort were provided by the M. DeMatteo Construction Company, and General Electric, with a later involvement by Wheelabrator Energy Systems Inc. in the form of a joint venture of the two firms under the name of Refuse Energy Systems Company (RESCO). The key element here was the fact that M. DeMatteo Construction Co. was the owner of a major landfill, which was the primary means of waste disposal for the majority of communities in the area, and this landfill was to be closed for environmental reasons. In order to continue providing the disposal service, DeMatteo sought other means of disposal.

This vital entrepreneurial effort was accomplished by private interests. Although the real loss would have been suffered by the communities using the landfill, they were spared the trouble and expense of the preliminary facility planning. It is understood that RESCO, the joint venture, now has nearly $10 million of equity invested in this facility.

A Guaranteed Source of Refuse--

The major investment required to construct a refuse-to-energy conversion plant demands that the source of refuse, the raw material for the plant operation, be assured as to quantity and availability. This seems like an elementary precaution, but it is too frequently overlooked or lightly considered in facility planning. Refuse collection in a city and surrounding areas is not always under municipal control and frequently the function is performed by many private firms with diverse interests.

RESCO obtained long term contractual agreements with ten nearby municipalities, including Saugus, to deliver their refuse to the new plant. This furnished a guaranteed minimum amount of refuse for operation of the facility, sufficient to justify proceeding with development plans. It also was an indication of much more refuse that would be available to the plant on similar contracts from other nearby communities, including parts of Boston. There should be no problem in obtaining enough refuse to operate the plant at the planned level and perhaps for a future expansion.

An Assured Source of Revenue--

If a refuse-to-energy project is to be a financial success, i.e., pay its own operating expenses and provide a return on capital, adequate revenues must be derived. Prudent planning requires that there be some assurance of an adequate level of revenue through some contractual agreement or arrangement with prospective users of the plant's services. If revenue bond financing is contemplated, reasonably firm agreements would be mandatory.

RESCO met the need for adequate revenue through (1) a drop charge to the using municipalities for disposing of their waste, and (2) a firm contract to sell steam to the General Electric Company, Lynn plant.

The refuse supply contracts with the neighboring municipalities contain a drop charge clause that sets the initial charge at \$14.33/Mg (\$13 per ton) and provides for escalation in accordance with an agreed upon formula. RESCO cannot arbitrarily raise the price.

When the refuse-to-energy concept was first conceived for this area, the General Electric Company was very much interested and supported the concept because they had found it would be necessary to replace two of their existing steam boilers. It was reasoned that it might be desirable to purchase steam from an outside source such as RESCO rather than invest in two new boilers. The result is a firm long term contract between G.E. and RESCO whereby G.E. is committed to purchase a minimum of 907 Gg (two billion pounds) of steam per year from RESCO. The RESCO plant is designed to produce steam at the temperature and pressure required by G.E. The selling price is based on a formula that includes an allowance for the probable plant investment, fuel cost, and labor cost for the new replacement boilers, which G.E. now does not have to buy. The price also contains a slight discount to G.E. to make it attractive and assure continuation of the arrangement beyond the existing contract.

The combined revenues from steam sales and drop charges, all firmly committed, are sufficient to operate the plant, make the lease payments to the town of Saugus, pay taxes, and afford a profit to RESCO. There is also income from the sale of recovered metals, mostly ferrous metal, but the financial success of the operation does not depend on it.

Technology--

No matter how well plans are made to receive sufficient refuse and produce an adequate revenue, no project can be successful if the chosen refuse-to-energy technology fails to perform as planned. At best, such failure could result in higher operating costs with reduced profit or even a loss resulting in default on bonds. At worst, it could mean a total failure to function. RESCO made certain that the processing technology would not cause trouble to the project by adopting a thoroughly tried and proven method of extracting energy from waste.

In this regard, it should be understood that Wheelabrator Energy Systems Inc. holds the American Rights to the Von Roll technology. This automatically determined the technology to be used for energy recovery early in the project development without expenditure of time and funds studying and comparing the various technologies available.

If a new project is to be funded by revenue bonds, as this one was, it is necessary that the energy recovery methods chosen not only appear to be technically feasible but it must be demonstrably so to the bond-buying public. Here too, the choice of proven Von Roll technology met the requirement.

Financing--

The financing of major resource recovery projects has been so frequently a major stumbling block to any further development that one might expect this aspect of project development to receive primary consideration. If the previously described development conditions, preliminary financing, source of refuse, source of revenue, and technology, have been thoroughly considered prior to any study of financing, the combined results should indicate clearly whether or not the project is financially feasible. If it is, there are several choices of financing methods available. Among them are general obligation municipal bonds, revenue type municipal bonds, and, more recently, the tax exempt revenue bonds that may be issued by an authority specially constituted for the purpose of constructing environmental protection and waste disposal facilities.

In this case, RESCO found that the project could be economically justified. The Town of Saugus created an Industrial Development Authority authorized by Chapter 40D of the General Laws of the Commonwealth of Massachusetts, which was empowered to issue industrial development revenue bonds on a tax exempt basis for the purpose of constructing solid waste disposal facilities. This authority initially issued $15,000,000 worth of short term bonds to secure funds for construction. Later, as the project approached completion, $30,000,000 worth of 20-year revenue bonds were issued with the proceeds used to complete construction, retire the original $15 million bond issue and pay back some loans made during construction.

The plant is owned, through the Authority, by the Town of Saugus, and is then leased to RESCO. The amount of the annual lease payment is sufficient to cover the interest and principal amount (debt service) on the bonds. RESCO is required to maintain a bond reserve fund equal to two years of debt service.

Financial Analysis

The RESCO facility has an installed capacity to process a maximum of 1361 MG (1,500 tons) of refuse per day with an average throughput conservatively planned at 1088 Mg/d (1,200 tons per day). An estimate by the Rust Engineering Company, the wholly-owned subsidiary of Wheelabrator-Frye who was the designer, made in May of 1975, places the gross cost at $38,268,000. This total consists of the following:

Land	$ 772,000
Site Development	1,302,000
Refuse Receiving and Handling	3,479,000
Refuse Combustion Building, Chutes, Grates, Furnaces, Etc.	13,018,000
Stand-by Boilers	610,000
Pollution Abatement Equipment	2,119,000
Ash handling and disposal	1,899,000
Boiler Feedwater Supply and Treatment	565,000
Utility Bridge	1,609,000
Utilities and Miscellaneous	917,000
Direct Construction Costs	$26,290,000
Indirect Costs	6,684,000
Real Estate Taxes	313,000
Construction Interest	2,099,000
License and Contracting Fee	1,455,000
Financing and Start-up Costs	1,427,000
Gross Requirement	$38,268,000

At this gross cost and an average throughput of 1088 Mg (1,200 tons) per day (397 Gg or 438,000 tons per year), the capital cost per Mg of daily plant capacity is $35,156 ($31,890 per ton).

The plant was designed for future expansion and RFSCO has made studies that indicate that the increased amount of waste to make expansion possible is available in the service area and there is also indication that G.E. could accept the increased output of steam. If the plant is expanded by the addition of one more 680 Mg (740 ton) per day rated boiler (544 Mg/d or 600 TPD avg), the gross cost is estimated by Parsons* as follows:

Land	$ NC
Site Development	50,000
Refuse Receiving and Handling	260,000
Refuse Combustion Building	7,000,000

Stand-by Boiler	$ 325,000
Pollution Abatement Equipment	1,100,000
Ash handling and disposal	400,000
Boiler Feedwater Supply and Treatment	100,000
Utility Bridge	NC
Utilities and Miscellaneous	100,000
Added Direct Construction Costs	$ 9,335,000
Indirect Costs	2,373,000
Real Estate Taxes	NC
Construction Interest	745,000
License and Contracting Fee	516,000
Financing and Start-up Costs	475,000
Total Added Costs (1975 Basis)	$13,444,000

*This estimate and the one that follows are entirely the responsibility of Parsons; the owners of the RESCO facility in no way contributed to the estimate or commented on their accuracy.

If this estimated additional cost for increased capacity is added to the $38,268,000 base cost, the total cost of a plant with an average daily capacity of 1633 Mg (1,800 tons) is $51,712,000, and the capital cost per Mg of daily plant capacity is $31,670 ($28,728 per ton). The reduction in capital cost per ton from $31,890 to $28,728 for an increase of 50% in capacity is quite modest, being only about 10%. The variation would be even less apparent if the present facility had been designed without consideration for future expansion. This suggests that at an average capacity of 1088 Mg (1,200 tons) per day, this type of refuse-to-energy plant has already realized most of the benefit of large size and that further increases can only result in nominal saving in capital cost per unit of capacity.

An estimate of probable project cost for a plant with half the capacity of the existing plant (544 Mg/d or 600 TPD average) is considerably more difficult to make because it involves changes in basic developmental costs as well as the deletion of costs related directly to capacity. Nevertheless, in order to illustrate the probable sensitivity of capital cost to plant size, the following Parsons estimate of cost for an average 544 Mg (600 ton) per day plant is presented. It is based, as are other estimates, on 1975 costs and on the cost structure developed for the existing plant.

Land	$ NC
Site Development	300,000
Refuse Receiving and Handling	1,730,000
Refuse Combustion Building	6,400,000
Stand-by Boiler	325,000
Pollution Abatement Equipment	1,055,000
Ash Handling and Disposal	400,000
Boiler Feedwater Supply and Treatment	265,000
Utility Bridge	NC
Utilities and Miscellaneous	200,000
Deleted Direct Construction Costs	$10,675,000
Indirect Costs	2,714,000
Real Estate Taxes	NC
Construction Interest	852,000
License and Contracting Fee	$ 590,000
Financing and Start-up Costs	550,000
Total Deleted Costs (1975 Basis)	$15,381,000

If this estimated cost deletion for reduced capacity is deducted from the $38,268,000 base cost, the total cost of a plant with an average daily capacity of 544 Mg (600 tons) is $22,887,000, and the capital cost per Mg of daily plant capacity is $42,052 ($38,145 per ton). This is a substantial cost increase per unit of refuse handled for a reduction to half of the capacity of the existing plant, being about 19.6%.

It can be seen from a comparison of capital cost per ton for the three plant sizes, i.e., 544, 1088, and 1633 Mg/d (600 TPD, 1,200 TPD, and 1,800 TPD), that the smallest plant suffers from the high cost associated with small size, while the largest one indicates a diminishing benefit from further size increases. A similar comparison should be expected in the range of operating and maintenance costs.

HAMILTON, ONTARIO

Introduction and Summary

The Hamilton Solid Waste Reduction Unit (SWARU) is owned and operated by the Regional Municipality of Hamilton-Wentworth, which maintains offices at Hamilton City Hall, 71 Main Street, Hamilton, Ontario, Canada. This facility recovers energy from waste by producing steam from shredded refuse in a water-wall boiler (incinerator), although there is currently no customer for the steam. The design capacity is 544 Mg/d (600 TPD) of refuse and 95 888 kg/h (211,400 lb/hr) of steam. It is located on level land a short distance from major industrial plants and the buildings are functional and neat in appearance.

SWARU has experienced several problems that are discussed in detail within this Section and immediately below. The important observation to be made is that refuse combustion technology is established and can yield reliable and economical conversion to energy when all conditions of proper design and equipment selection are met.

Conclusions

- All waste-to-energy processing plants have rather high capital costs per unit of capacity, and it is therefore essential to maintain the design throughput. With problems in any one of the several processing steps able to markedly affect operating capacity, the design and financing must be realistically accomplished as a total system. SWARU was basically conceived of as a waste disposal system and different features would now be incorporated if it were to be designed today as an energy recovery facility. The semi-suspension moving grate combustion system used is rather unique for MSW and this plant has verified the approach is a sound one. Location of a customer for the steam produced would of course greatly improve plant economics.

- Compromises made in the materials handling equipment have been the cause of part of the reduced capacity at Hamilton. Thorough testing, preferably at full scale, should always be made when design changes are added and equipment suppliers should be notified on all pertinent characteristics of the waste and interface units. The materials handling equipment at SWARU can be improved, as can the marginal air pollution control efficiency, but installation of the proper equipment originally is always far less expensive than retrofit costs.

Process Description

A schematic process flow diagram is presented as Figure 2, where a step-by-step description of the process as it was originally designed is shown. The changes and modifications to the process that have been made to bring it to its present operating condition are discussed separately.

The process begins with the arrival of a refuse collection truck at the automatic recording scales, Item 1 on the flow diagram. At this point, the

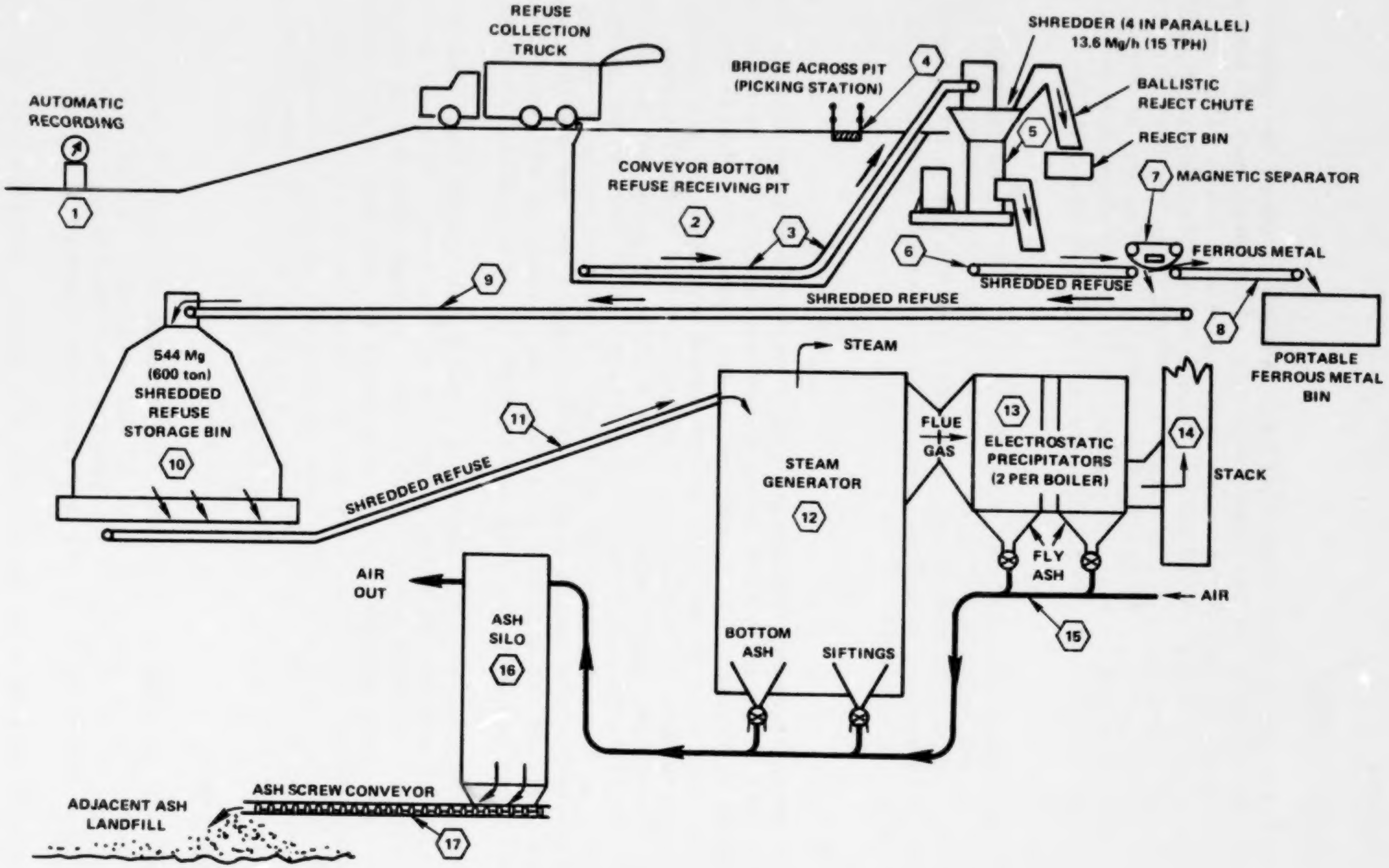
AUTOMATIC RECORDING
1
REFUSE COLLECTION TRUCK
CONVEYOR BOTTOM REFUSE RECEIVING PIT
2
3
BRIDGE ACROSS PIT (PICKING STATION)
4
SHREDDER (4 IN PARALLEL) 13.6 Mg/h (15 TPH)
5
BALLISTIC REJECT CHUTE
REJECT BIN
7
MAGNETIC SEPARATOR
6
SHREDDED REFUSE
FERROUS METAL
8
PORTABLE FERROUS METAL BIN
9
SHREDDED REFUSE
544 Mg (600 ton) SHREDDED REFUSE STORAGE BIN
10
11
SHREDDED REFUSE
STEAM
STEAM GENERATOR
12
FLUE GAS
13
ELECTROSTATIC PRECIPITATORS (2 PER BOILER)
14
STACK
FLY ASH
AIR
15
BOTTOM ASH
SIFTINGS
AIR OUT
ASH SILO
16
ASH SCREW CONVEYOR
17
ADJACENT ASH LANDFILL

Figure 2. Schematic process flow diagram of the Hamilton Solid Waste Reduction Unit.

load is automatically weighed and remotely recorded for plant operating records and billing purposes. The operation is under surveillance from the central control room by closed circuit TV, and further truck movement is directed by a system of traffic signals, also controllable from the central control room.

From the scales, the truck proceeds to the receiving building, entering by either of two inclined ramps, and discharges its load into the conveyor bottom receiving pit, Item 2. When unloaded, the truck leaves the building via one of two exit ramps. Truck movement, except for backing and dumping, is a straight-through "one-way" operation. In the event of an emergency, a small amount of space exists at the truck level where loads of refuse can be dumped directly onto the floor and later moved into the pit by a dozer or front-loader. Such use of the floor is reserved for emergency situations only, in order to hold down maintenance costs resulting from blades damaging the special corrosion-resistant asphalt layer on the concrete slab.

The refuse in the pit is moved toward one end and up a steep incline by four parallel metal pan conveyors, Item 3, upon which all the refuse rests. The steep incline serves to limit the amount of waste on the conveyors as they leave the pit, and, of course, the change in elevation is necessary in order for the refuse to be transferred from the pit to the shredder.

As the refuse moves slowly up the incline, it passes under a bridge over the pit, Item 4, from which one or two men using rakes and pitch forks smooth out the flow and remove all excessively bulky wastes. The items removed are deposited in two nearby roll-off bins and subsequently sorted for direct salvage or landfill.

Each of the four pit conveyors delivers refuse to a 13.6 Mg/h (15 TPH) vertical shaft shredder, Item 5. These shredders reduce the refuse to approximately 5 cm (2 in.) size or less. With four 13.6 Mg/h (15 TPH) shredders in parallel, the total rated plant capacity is 54.4 Mg/h (60 TPH). It is characteristic of vertical shaft shredders that some difficult-to-shred materials such as iron parts and some rock will be struck by the first whirling breaker bar and rejected up the ballistic chute. This rejected material is collected from each shredder in a small bin and taken to the main receiving floor, where it is hand-sorted for salvageable metals, inert materials for landfill, and combustibles to be returned to processing.

The shredded refuse from all of the shredders is collected on a single-troughed belt conveyor, Item 6, and conveyed to a magnetic separator, Item 7. The separate mechanism requires a new belt about every 3 months, necessitated by occasional jams in the feed chute. After magnetic separation, the refuse stream splits, with the separated ferrous metal (containing up to 5% organic material) conveyed via a troughed belt conveyor, Item 8, to a roll-off bin outside the building. The remaining shredded material, which can now be considered as fuel, is conveyed on a troughed belt conveyor, Item 9, outside the processing building to the storage bin, Item 10.

The shredded fuel is accumulated in the beehive-shaped storage bin, reclaimed automatically by built-in equipment, and conveyed via trough belt conveyor, Item 11, to the two Babcock and Wilcox "Stirling" waterwall steam generators, Item 12. Not shown is a flow divider, provided as part of the fuel conveying system inside the boiler house to proportion the fuel flow to the steam generators. The present flow divider is being rebuilt to allow manual control for the fuel flow. This will improve control over the volume of refuse to each generator.

Flue gas leaves each steam generator at a nominal 286°C (547°F) and passes through a two-field Lurgi-design electrostatic precipitator, Item 13, before exiting to atmosphere through a 50 m (165 ft) high stack, Item 14. Incomplete combustion of flue gases during start-up or when burning excessively wet refuse tends to increase visible stack emissions and the increased emissions persist until proper operating temperatures are reached in the boilers. Steam is generated at 1.82 MPa (250 psig), saturated. Some of the steam is used to drive plant auxiliaries such as conveyor drives, but most of it it condensed in air cooled condensers on the roof and the condensate is returned to the boiler. SWARU reports that the air cooled condenser tubes have recently been leaking profusely. The problem is under investigation, and a solution is being sought. Continuing leakage results in increased costs for water conditioning chemicals, and can also lead to serious structural problems on the roof when the flow of water causes ice masses to form.

Bottom ash and siftings from the boiler grate are designed to be removed to a silo, Item 16, by a steam-driven pneumatic transport system, Item 15. The large volume of the silo is intended to slow the moving air and thereby allow the ash to drop out before the air exits to the atmosphere. The fly ash silo is currently not in use because (1) the fly ash and bottom ash differ so much in their characteristics that common removal becomes very difficult; and (2) the fly ash is so fine that it does not settle in the silo, but escapes and disperses in the open air. A report is being prepared for modifications to the in-plant ash collection system in order to make it operative.

The last item in the process chain is a belt conveyor, Item 17, which removes ash from the silo and conveys it a short distance to an adjacent landfill. It is estimated that the landfill can be used until late 1977. After that, the ash residue will have to be disposed of elsewhere. Additional uses or means of disposal are under investigation.

Processing Equipment

Refuse Receiving Pit--

This concrete pit, built as part of the building structure, is 12 m wide by 30 m long by 9 m deep (40 x 100 x 30 ft). The top level of the pit from which the trucks dump their loads is about 4.6 m (15 ft) above the level of surrounding terrain.

Conveyors (Item 3)--

The bottom and one end of the refuse receiving pit are completely covered by four parallel metal slat conveyors, each powered by a 11.2 kW (15 HP) motor. A 18.6 kW (25 HP) motor was installed to alleviate a problem of stalling of the conveyors under full load. Its performance proved satisfactory and three 22.4 kW (30 HP) motors have been ordered to replace the remaining

15 HP units. The bottom horizontal sections merge into the inclined, 45-degree end section without any break. Therefore, the bottom part, which may have a 9 m (30 ft) depth of waste on it, moves just as fast as the inclined end part, which has only 30 or 60 cm (1 or 2 ft) of waste on it.

Shredders--

The Item 5 shredders are 149 kW (200 HP) vertical shaft machines rated at 13.6 Mg/h (15 TPH). These are Tollemache machines sold in the United States and Canada by the Heil Company; they are basically vertical hammermills with a part of the mill set to relatively close clearance for some grinding effect. All waste is shredded in a single pass to less than 5 cm (2 in.) size. There is no secondary shredding.

Other Conveyors--

With the exception of the receiving pit conveyors and the pneumatic ash removal system, all conveyors used in the facility are heavy duty troughed belt conveyors built on truss-type frames. None are fully enclosed for dust control, but all have some form of hood or enclosure. Conveyor belt widths are appropriate to the quantity of material to be handled. Some of the conveyors are steam turbine powered, using the available plant steam.

Shredded Refuse Bin--

This patented unit has a storage capacity of 544 Mg (600 tons), equivalent to 24 hours full-rated operation of the steam generators. The beehive shape and 21.3 m (70 ft) diameter circular base of this steel bin are intended to prevent any bridging of material. Serious bridging and binding problems have occurred, however, in the Atlas tank. A proposal by the manufacturer suggests that a hollow center cone and a swinging feed chute at the top of the tank would solve this problem. The proposal is under consideration.

The Atlas reclaiming system utilizes a heavy duty chain around the perimeter of the bin, held in place on a recessed track, and driven at a controllable variable speed. This chain, in turn, tows three or more chain and bucket assemblies that drag on the floor of the bin and tear at the toe of the piled material. The dragging action of the bucket assemblies has produced more wear and tear on the concrete floor of the bin than anticipated, a 25 cm (10 in.) deep groove in the floor thus far. The material drawn from the pile is dragged across the bin bottom to a grating through which the material falls to a conveyor below. This conveyor discharges to the transport conveyor, Item 11, which carries the shredded fuel to the boilers. Metering of fuel output is accomplished through controlling the speed of the chain and bucket assemblies.

Boilers--

There are two Babcock and Wilcox "Stirling" power boilers, Item 12, each rated to burn 272 Mg (300 tons) of shredded refuse per day, producing 47,944 kg/h (105,700 lb/hour) of steam at 1.82 MPa (250 psig), saturated. This rating and a 71 percent actual design efficiency are based on an assumed higher heating value of the refuse of 13.96 MJ/kg (6,000 Btu/lb). The use of shredded refuse in a water walled boiler of this type allows efficient operation with only 37 percent excess air. The application of an electrostatic precipitator for particulate removal becomes practical and comparatively economical in conjunction with this reduced quantity of flue gas and the use of a small economizer to reduce flue gas temperature to 310°C (590°F).

Figure 3 is a schematic section through this type of boiler as applied to burning shredded refuse. The shredded refuse enters the boiler house from the storage bin via a conveyor near the top of the boilers. At this point, a proportioning device distributes the refuse to one or both boilers, as required, and the refuse thus proportioned is further divided among three vertical chutes on the face of each boiler by a swinging spout device. The refuse drops by gravity to a point just above the grate and there is blown into the fire box by a blast of air. The lighter parts of the shredded refuse burn in suspension very quickly, while the heavy parts and inert materials fly to the opposite side of the fire box and land on the grate. These heavier parts are carried on the slowly-moving grate toward the front of the furnace, the speed being adjusted to allow time for burnout with a relatively thin bed of burning material. After final burn-out, the ash drops into the bottom ash pit. A portion of the burned material from the grate sifts through it and drops into the combined air plenum and ash hopper directly below, but this normally contains little remaining combustible matter.

The over-fire feeding of shredded refuse with a high percentage burned in suspension makes it possible to maintain a relatively constant furnace temperature and prevent hot spots and slagging. The suspension burning plus the resulting thin bed on the grate allows efficient operation with minimum excess air without creating a reducing atmosphere near the tubes. Because of these advantages, it is not necessary to provide refractory protection of the lower boiler tubes and a steadier steam rate can be maintained. The design efficiency of this boiler installation, even at the comparatively low operating pressure, is 71 percent. Unburned light fractions of refuse, especially paper, have been found in the precipitated fly ash. A proposal has been submitted for the installation of auxiliary air jets to provide over-fire air in a vortex effect, which would serve to ensure complete combustion of materials in suspension.

The remainder of the steam generating installation is essentially a standard water tube boiler, except that the use of refuse as a fuel requires a somewhat larger installation than would be required to achieve the same output rating with a fossil fuel.

Air Pollution Control--

The electrostatic precipitators are Wheelabrator-Frye "Lurgi" design units of the two-field type, designed for inlet conditions of 38.2 m^3/s (81,000 ACFM) of flue gas at 307°C (585°F), with a particulate loading of 0.533 wt-% (on a volumetric basis, 3.18 g/m^3 or 1.5 grains/SCF) corrected to 50% excess air. Design outlet loading is 0.008 wt-% (0.05 g/m^3 or 0.0225 grains/SCF), for an efficiency of 98.5 percent. Specific collection area is 0.67 m^2/m^3 (215 $ft^2/1000\ ft^3$) of gas.

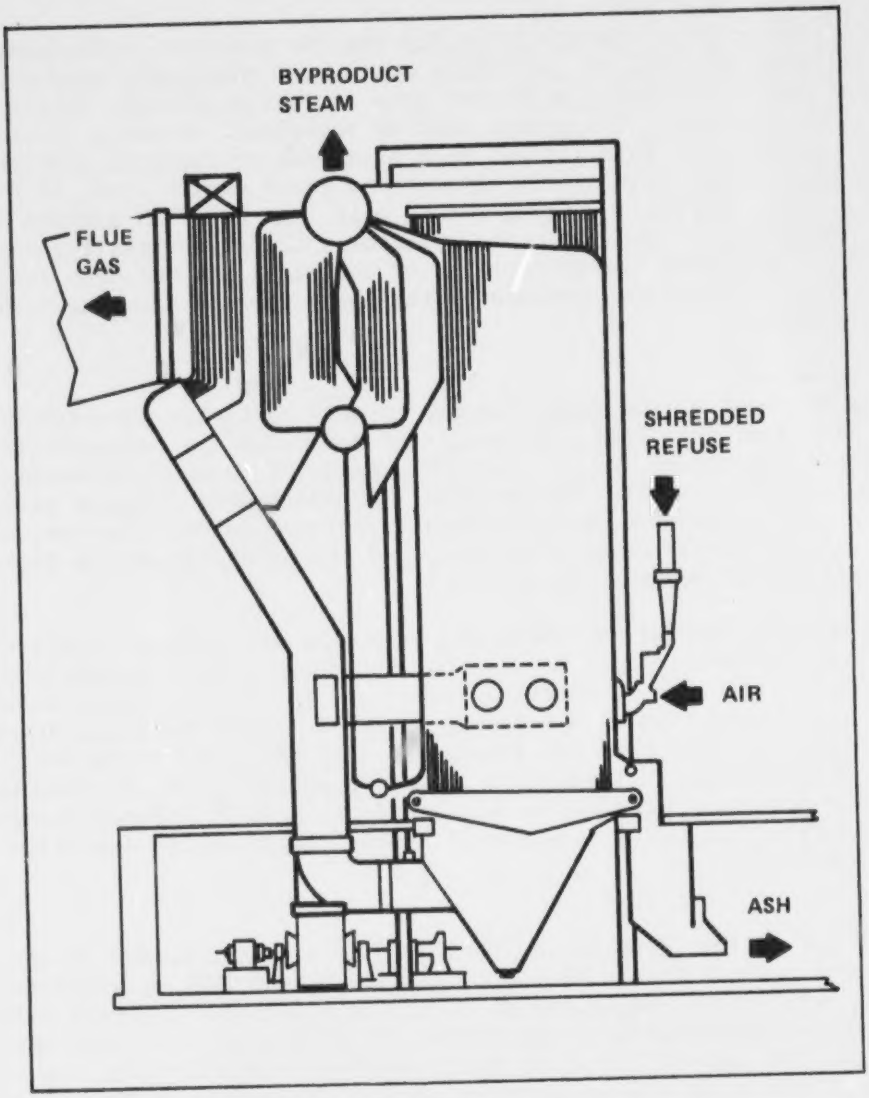
BYPRODUCT STEAM
FLUE GAS
SHREDDED REFUSE
AIR
ASH

Figure 3. Schematic section of refuse-fired boiler at the Hamilton Solid Waste Reduction Unit.

Existing Operation

Actual Capacity Realized--

A matter of some concern initially was the probable performance and reliability of the boilers, but these units have thoroughly proven themselves. There has been no evidence of boiler tube corrosion and very little need for maintenance shutdown. The grates need an occasional cleaning to remove grit from the joints, but this has not been a serious or frequent problem. The boilers have demonstrated their capacity to reach design load, or even a moderate overload, while burning refuse only. At least 50 percent of burning is in suspension, according to the operators, though no test figures are available. The total design capacity of the plant has not been realized, except for short periods, because of various materials handling problems discussed below.

Receiving Pit--

The conveyor bottom receiving pit is only partially successful. If the pit is filled or near full, the weight of refuse on the conveyors is too great and the driving motors stall. The replacement of these 15 HP motors with 30 HP motors should solve this problem. An additional conveyor problem is that they must be stopped due to operational problems. When restarted, the conveyors may run freely under the waste, and the bridging must be broken with an electric hoist mounted over the pit.

At present, refuse is dumped only into the one-quarter to one-third of the pit nearest the incline feeding the shredders. This reduces the load and the conveyors are able to function properly. The steep incline at the end of the pit apparently acts as a metering device to limit the depth of refuse on the conveyors as they feed the shredders. The inability to maintain a pit full of refuse makes it impossible to extend operation of the shredder much beyond the normal working day of the refuse collectors without storing more refuse at the truck level than was intended. This is one limitation on total plant capacity.

Shredders--

The use of four 13.6 Mg (15 TPH) shredders, which cannot accept oversized waste, rather than a single large 54.4 Mg (60 TPH) shredder capable of accepting all wastes, was based on an economic decision that the bulky material could be separated and land-filled for less total cost than the difference in cost between the four small shredders and one large one. There was also a desire to use equipment available in Canada, as these Tollemache machines were. Data that would prove the merit of this decision are not available, but there are some design and operating problems that apparently result from this decision. These are:

- The use of multiple shredders demands some form of multiple feed such as the conveyor bottom pit, which is not functioning properly at present.

- The smaller shredders require a much closer control of feed to prevent overloading and to assure that large items do not slip through.

- The shredded refuse from these machines and of the bottom ash from the boilers are observed to contain some refuse items that are hard to shred, such as tough rubber products and leather-like plastics. These seem to get through in much larger pieces than the supposed 5 cm (2-in.) maximum. Whether this is a fault of the machine size, type, or maintenance is not known.

- In a refuse-shredding operation where ferrous metals are to be recovered by a magnetic separator, the ballistic reject feature of the vertical shaft shredder serves no useful purpose. It only causes a labor problem in moving and sorting the bins of rejects.

Shredded Refuse Storage Bin--

The greatest single cause of reduced capacity, lost manhours, and general uncertainty of operation has been the shredded refuse storage bin. Although the Atlas bin reclaim system has reportedly performed satisfactorily in other installations, it is not functioning properly here. This apparent contradiction prompted an investigation to learn what the faulty operation really was, and, if possible, why it was faulty. The major problems that have occurred are outlined below, followed by a brief history of the engineering, fabrication, and modification of the storage system. A comparison of the two will clearly show why the faults occur. Some of the problems are:

- The packed refuse at the bottom of the bin is very difficult to scrape free and the reclaiming apparatus is unable to handle it, except at a slow rate.

- If the reclaiming apparatus is speeded up to gain more output, a chain failure is likely.

- If, for any reason, the shredded refuse is allowed to remain in the bin for more than 24 hours, it begins to decompose. This adds to the tendency to pack and the consequent difficulty of removal. In addition, this change in refuse characteristics is reported to increase the density of the material, rendering it more difficult to handle and burn. Most importantly, the incineration of such refuse appears to result in higher stack emissions.

- There has been a tendency for the shredded refuse to bridge in the bin. This has nothing to do with the shape of the bin; the shredded refuse tends to pack down and bridge within itself when attempts are made to extract it. The sweep buckets compress the material in an inward radial direction, resulting in formation of a hard core in the center of the tank. In addition, lighter materials, such as paper, tend to be more readily removed by the sweep buckets while other materials are not removed. These remaining materials become compacted and interwoven, effectively forming a single semi-solid mass.

- The operators report excessive floor and bucket wear.

When the reclaim system was under design, the vendor was provided with samples of shredded refuse upon which to base his design. These samples indicated a maximum particle size of about 5 cm (2 in.), but in practice this size is more likely an average, with much material such as rags, plastic, rope, wire, and the like considerably oversize or hardly shredded at all. The vendor states that had he been aware of this, the design would have been different and would perform much better in extracting waste from the pile. The larger pieces, particularly fibrous materials such as rags, tend to remain behind and bind the remaining shredded material into a tightly packed mass.

In an attempt to reduce the capital investment, a steel center cone that directs waste toward the periphery of the bin and prevents buildup of a hard central core, was omitted. The hard central core does built up, as predicted, and must be removed periodically by hand.

The designers of the plant wanted to drive as much of the equipment as possible with steam and in order to do this with the bin reclaim system, the plant designers provided a dual steam turbine drive. This replaced the sophisticated, dual DC motor, variable speed, load-sharing drive and control system normally provided by the vendor. Turbine controls have never functioned properly to share the load between two turbines, and speed control is possible only over a limited range, rather than the 20 to 1 range normally provided. When load sharing between the two drive turbines proved to be impossible, one turbine was disconnected and the reclaim system is now driven by only one. This more than doubles the load on the turbine and the pull of the chain. This is an obvious explanation for the frequent chain breakage.

There is no explanation for the reported excessive wear on the floor and buckets other than the fact that the waste contains a certain amount of glass, dirt, and rocks, and is therefore likely to be quite abrasive.

Although the Hamilton area experiences cold winters, freezing of the material in the bin has not been a problem. This is possibly due to the good insulating properties of the shredded material and to the internal heat generated by decomposition.

Ash Removal--

Both bottom ash and fly ash were originally planned for removal by the same pneumatic system. No part of this system is presently in use. The problems were:

- The bottom ash frequently contained large pieces of refuse that had not been shredded to specification and these oversize pieces plugged the pneumatic transport pipe. At present, a belt conveyor is used to remove bottom ash from a small quench tank. This belt dumps the ash on the ground where a bulldozer pushes it onto a landfill area.

- The air velocity in the pneumatic system was too low to entrain and transport the heavier ash particles.

- There was no cyclone separator or bag house to trap the lighter particles of ash, so these particles, mostly from the fly ash, did not settle out in the ash silo as planned, but were exhausted to the atmosphere. Several methods of fly ash removal have been tried, but without marked success. This remains an annoying problem, but it does not affect the overall capacity of the plant.

Electrostatic Precipitators--

There is reason to believe that the specification on the precipitators would have to be more stringent for future installations. There is no data available on actual stack emissions, but observations by Parsons employees and others indicate more visible emissions than could be tolerated on new installations.

Ferrous Metal Recovery--

The ferrous metal recovery equipment is adequate and working well. There is no available data on the percentage of recovery achieved, but the actual quantity of metal recovered is greater than had been expected on analysis of refuse during the planning phase of the project.

Dust Control--

Most of the conveyors and mechanical equipment have some form of hood or cover, but there is no real dust control system. The result is that the plant is dusty and requires frequent cleanup. A part of the dust problem can be attributed to the ineffective fly ash removal system.

Engineering Comments

In the foregoing sections, the process and plant equipment were described and the operation was discussed. Most of the faults and problems are susceptible to correction and this facility may yet become an efficient refuse-to-energy operation.

The operating problems have not prevented utilization of the plant, but have forced it to operate at reduced output and with the expenditure of more manpower than would otherwise have been necessary. Each of the problems in operating this facility is discussed in detail below for the purpose of learning from this experience and to suggest some possible improvements or corrections.

Pit Conveyor Failures--

The inability of the pit conveyors to function properly when the pit is well filled seems to be caused by the fact that the bottom section, which is in one unit with the inclined section, must operate at the same speed as the inclined section. This forces it to scrape under the deep pile of refuse because the pile cannot move as fast and also tends to ram the refuse very hard against the inclined conveyors, such that the former could be much slower than the latter. The ratio of speed could range from 1 to 3 to 1 to 30. With this one change, admittedly not an easy one, it should be unnecessary to replace all conveyors with heavier units.

The operators of the plant, however, do not believe that slowing the bottom conveyors with respect to the inclined conveyors would work properly. Instead, they feel that the heavier duty 22.4 kW (30 HP) motors, will provide the power necessary for successful conveyor operation.

This concept of a small refuse receiving pit could be a very successful design if some of the suggested improvements were made in the conveyor system. These same improvements have been incorporated in conveyor designs and in published promotional material by the original vendor of the conveyors (Ref. 1).

Shredders--

The four relatively small shredders have not, in themselves, been a problem, but their use forces the operators to provide personnel to pick bulky waste and difficult-to-shred items from the waste. The income from ferrous metals salvaged directly from the pit is insufficient to support the additional manpower required, but this activity is required to protect the shredders from potential damage. A system of selective refuse collection is presently under consideration, in an attempt to minimize this problem. The ballistic reject feature of these small shredders seems of doubtful value.

The most disturbing thing observed concerning the performance of the shredders is the excessive amount of material that passes through the machine with little or no shredding. The larger unshredded pieces tend to increase the percentage of unburned combustible in the bottom ash, causing some difficulty in ash handling, and creating a problem in the operation of the shredded refuse storage and reclaim system.

This problem possibly can be rectified by improved shredder maintenance and by a closer setting of the machine for a finer shredded output, but it seems probable that the only dependable correction would be to replace the existing shredders. Normally, shredding to a maximum of 5 cm (2 in.) is accomplished in two stages. In this case, the 544 Mg/d (600 TPD) capacity at the desired size could probably be reached by a single large shredder operating for two shifts. In effect it would be 54.4 Mg/h (60 TPH) shredder de-rated by one-third to accommodate the fine shred. The type of machine is open to consideration, but the trend seems to be toward the horizontal hammermill.

It would be possible to modify the existing operation to install such a machine, but it would be difficult and costly to do so. It would be necessary to weigh the potential benefits very carefully.

Although setting the shredders to produce a finer output may, to some extent, remedy some existing problems, this would also significantly increase the maintenance requirements of the shredders. The use of a single large shredder would appear attractive until one considers the additional equipment, such as hoists, required to service such a unit. In addition, a breakdown of the only shredder in the plant could cause operations to cease until the problem was remedied.

Dust Control--

The plant has no effective dust control and the result is a poor working environment. There does not appear to be any single piece of equipment or operation that produces large quantities of dust. All of the conveyors are covered or hooded, as are the shredders, but there is no means of drawing off the dust that accumulates inside the enclosures.

A dust intake hood could be provided over the pit and all conveyor and shredder housings could be placed under negative pressure to draw off dust, but the required equipment would cause this to be a relatively expensive plant improvement. The lack of dust control does not interfere with operation of the plant, but there is some suspicion that it is a contributing factor to a fairly high absentee rate.

The Shredded Refuse Storage Bin--

There does not appear to be any easy, inexpensive modification that could be made to improve the operation of the shredded refuse storage and reclaiming system. Since the problems with the system seem to stem from the fact that some elements of the storage and reclaiming system were never installed, the obvious solution is to complete the installation to the manufacturer's designs and recommendations. This means installing a center cone; installing the complete two-motor, DC, variable speed drive and control system; and, if possible, revising the bucket and chain reclaiming design to improve performance with the larger size shredded material now being processed. All this would be quite expensive, but, if the plant were ever to be able to meet a steam demand, it would have to be done.

Selling steam from this plant was not considered to be an essential feature. The SWARU was conceived strictly as a refuse burning facility. At present, the storage and reclaiming system has been by-passed and the shredded refuse is conveyed directly to the boilers to be burned.

Boiler Performance--

The boiler performance has been very satisfactory, with a relatively low demand for maintenance. It is unfortunate that there have been no tests to verify boiler efficiency and to measure the relative amounts of waste burned in suspension and on the grate. Even if manpower and funds were available to make such tests, the program would have to await improvements in the fuel handling system so that sufficient control of fuel supply over an extended testing period could be maintained.

The plant has operated since the summer of 1972, and in 1975 the total throughput was 43 Gg (48,000 tons), only about 22% of design capacity. This might seem to be very light duty and therefore easy on the boilers, but the material handling problems have caused many shutdowns and startups, severe service for any boiler. There is little evidence of any corrosion that might be expected to result from this.

The boilers use a gas burner to maintain a dependable steam supply for steam-driven auxiliaries, and the burner continues to operate at a low level while burning waste. With this type of boiler in continuous operation on shredded refuse, it should be possible to shut off the gas burner completely without serious consequences. Much depends upon a dependable continuous supply of shredded waste fuel.

Ash Disposal--

The disposal of ash from boiler operations remains a problem, though it does not affect the performance of the plant. The pneumatic system cannot be used to remove bottom ash unless there is some change in shredding technique to assure size reduction of all waste material to a maximum size equivalent to the handling capacity of the pneumatic equipment. The existing bottom ash handling modification involving a small quench tank, belt conveyor, and disposal area seems to be the best system under the circumstances.

The removal of fly ash could be accomplished by the pneumatic system with some modifications and improvements. These are:

- Air velocity must be increased, to be certain to entrain all particles of ash and keep them moving in the pneumatic tube.
- Equipment must be provided to separate the ash from the air at the storage silo. To meet stringent air quality rules, this should consist of a small diameter, high efficiency cyclone and an automatic shake-down bag filter. The use of the cyclone ahead of the bag filter will keep the filter size down and none of the equipment need be large and costly. The required air flow is not very high.
- The fly ash system will probably require some simple form of cycling control to sequentially discharge each hopper into the system.
- The use of a vacuum type pneumatic system, rather than a pressure type, will ensure that the ash does not escape, but remains in the system. This should materially improve the cleanliness of the entire plant.

None of the above suggestions solve the problem of what to do with the dry fly ash after it is collected in the silo. The silo is on the edge of the landfill, and the ash is currently dumped directly on the landfill area. As the available landfill reaches capacity, consideration will have to be given to trucking the ash away. There is a belt-type conveyor in place for transporting the ash to the fill and it is understood that the operators have tried introducing water at this point to hold down dust, but the resulting mix is too heavy for the belt conveyor.

Environmental Considerations--

The environment is affected by stack emissions, blowing ash, and truck traffic into and out of the plant. The ash problem has already been discussed in detail and the truck traffic is no real problem because the plant is in a rather remote industrial area. There is no apparent sound or noise from the plant. On occasion, however, a whistling was heard outside the plant when boiler pressure dropped. A change in the pressure relief valve solved the problem. The only external indication of plant operation is a very minor plume from the stack. During an inspection by Parsons of the facility, all four shredders were in operation, all conveyors were operating, the storage and reclaim system was working, and one boiler was in service. The operation of the shredders was barely detectable in the offices no more than 30 m (100 ft) away in the same building.

In spite of the existence of a precipitator with a rated efficiency of 98.5 percent, there were some visible emissions from the stack. This would not be acceptable performance in any new installation. There is no apparent reason for the visible emissions based on design ratings and assumptions, but there have been no tests to determine whether or not the particulate emission from the boilers is within the range for which the precipitators were designed.

The operators report numerous problems with the precipitators, including clinkering, plugging, and plate distortion. The reasons for these problems are unknown, but certainly the erratic boiler operation must be a contributing factor.

Steam Turbine Drives--

There are many pros and cons on steam turbine drive for plant equipment. Their use may seem attractive from the standpoint of reducing reliance on expensive external fossil fuel-generated power, but it must be realized that maintenance will be higher and control is not as easily accomplished as with electric drives. The operators of this plant are continuing to use the steam turbine conveyor drives provided with the plant design and do not have any adverse comments. The shredders are not steam-driven, but unless the large power-consuming devices, such as shredders and boiler draft fans, are steam driven, there will be little saving in electric power cost. The serious problem created by steam turbine drives on the storage bin reclaiming system has already been discussed.

Auxiliary Fuel--

This plant uses gas as an auxiliary fuel for start-up, for keeping boilers hot during periods of low refuse availability, and to maintain a reasonably steady boiler operation. The reported fuel costs for 1975 indicate a gas consumption equivalent of approximately 10 percent of the full boiler rating. This seems quite high, but is undoubtedly due to the erratic performance of the refuse fuel handling and storage system. When this system is improved, gas consumption will certainly be reduced.

Steam Sales--The Hamilton Incinerator Project (SWARU) was developed with the intent that eventually the steam produced might be sold for revenue, but the project proceeded without any specific steam customers. To date, there has been no attempt to sell steam, and no distribution system exists. For this reason, the plant has never been called upon to demonstrate its ability to match steam output to a demand. This is probably fortunate, because the poor performance of materials handling and storage systems would have made good control of steam output exceedingly difficult. Nevertheless, the performance of the boilers with the shredded waste indicates that good demand matching should be practical without excessive use of auxiliary fuel, provided that the fuel handling problems are solved.

Financial Analysis

A meaningful financial analysis is difficult to prepare since steam has not been sold and the materials handling problems have prevented operation at an efficient level. If these two important factors are entered into the analysis by means of assumed figures, then some indication of the financial potentialities of such a project might be obtained.

Capital Costs--

The owners report a capital cost of $9 million when the plant was completed and went into operation in mid-1972. If an identical plant were to be placed in operation in early 1976, the capital cost would have escalated by a factor of 1.6 to about $14,400,000.

As previously stated, it is unlikely that another plant would be built today to this same design; however, it is believed that improvements in shredding, materials handling, shredded refuse storage, ash handling, and dust control could all be realized for about one million dollars. These changes, though quite costly, would so drastically improve the operation as to pay for themselves in a short time.

A further important consideration in evaluating the financial feasibility of such a plant is the potential revenue from the steam produced. In order to make this revenue possible, it would be necessary to construct a steam distribution system to transport the steam to potential customers. There are no real data on this possibility, but there is some indication that, when a reliable steam supply can be assured, customers for the steam output can be developed within no more than 3.2 km (2 miles) of the plant. Such a steam distribution and condensate return system is likely to cost three to four million dollars at 1976 prices. For the purpose of a conservative financial analysis, a $4,000,000 figure is assumed.

The total 1976 cost for a fully operating 544 Mg/d (600 TPD), water walled, revenue-producing incinerator in the manner of Hamilton can be derived as follows:

Original 1972 Cost	$ 9,000,000
Escalation to Early 1976	5,400,000
Plant Improvements	1,000,000
Steam Distribution System	4,000,000
Total 1976 Cost	$19,400,000

If the owners and operators of Hamilton make the necessary improvements and install a steam distribution system, their total investment will be as indicated above, less the escalation figure, or $14,000,000.

Operation and Maintenance Costs--

As might be expected, the erratic operation of the plant has resulted in an apparently high requirement for manpower to operate it and some unnecessarily high expenses. The total operating staff during 1975 numbered 51 and was organized as follows:

Manager:	1
Chief Engineer	1
Maintenance Clerk:	1

Receptionist:	1
Shift Engineers (Class II):	4
Shift Engineers (Class III):	4
Shift Engineer Helpers:	4
Floormen:	5
Laborers	21
Mechanics	3
Electricians:	2
Maintenance Helpers:	3
Welder:	1
TOTAL	51

The poor operation of the materials handling and ash handling equipment shows in the large number of laborers, floormen, and maintenance people required. It is likely that with equipment improvements, the plant could reach full capacity with no additional help and might perhaps operate efficiently with fewer people.

The approximate 1975 operating and maintenance costs are as follows:

Labor	$605,000
Water	12,000
Power	42,000
Fuel	203,000
Chemicals	6,000
Equipment Maintenance	236,000
Building Maintenance	13,000
New Equipment	55,000
Equipment Rental	28,000
Miscellaneous	13,000
Debt Repayment	904,000
TOTAL	$2,117,000

This total operating and maintenance cost was generated while disposing of a total of 43.5 Gg (48,000 tons) of solid waste. This is a disposal cost of $48.62/Mg ($44.10/ton), a very high figure. It is offset only by a relatively small revenue from the sale of recovered ferrous metals. This will be discussed in a following section.

At 85 percent of design capacity, this plant should be able to dispose of 168.86 Gg (186,150 tons) of solid waste per year. With this rate of throughput, the operating and maintenance expenses would be increased, but not in proportion. An estimate of operating cost at the higher throughput is indicated below.

Labor	Unchanged	$ 605,000
Water	Increased proportionately	46,538
Power	Increased proportionately	162,881
Fuel	Doubled	403,000
Chemicals	Increased proportionately	23,269
Equipment Maintenance	No Change	236,000
Building Maintenance	No change	13,000
New Equipment	Accounted for in added debt	-
Equipment Rental	Doubled	56,000
Miscellaneous	Doubled	26,000
Debt Repayment	Existing debt - no change	904,000
Debt Repayment	Plant Improvements at $1,000,000, 11-1/2%, 10 years	173,377
	TOTAL EST. O & M	$2,649,065

At the annual potential throughput of 168.86 Gg (186,150 tons) and the slightly increased O & M cost, as delineated above, the disposal cost drops to $15.69/Mg ($14.23 per ton) of solid waste before taking any credit for possible revenues. This forcefully demonstrates how seriously the faulty operation of a few items of equipment has affected the cost of waste disposal.

The largest single item of O & M expense is the repayment of debt. At 43.5 Gg (48,000 tons) per year, this accounts for a disposal cost of $20.76/Mg ($18.83 per ton), while at 168.7 Gg (186,000 tons) per year it is only $5.36/MG ($4.86 per ton), a substantial difference. This alone illustrates how much benefit could be obtained by an added expenditure of funds to secure improved plant operation and a greater throughput.

Net Operating Cost--

The annual 1975 operating and maintenance cost was $2,117,000, which is equivalent to $48.62/Mg ($44.10 per ton) of waste handled. This can only be reduced by the $1.10/Mg ($1.00 per ton) revenue received from ferrous metal, or a net of $47.51/Mg ($43.10 per ton). This is the present situation.

If the improvements suggested are made to increase plant utilization to 85%, the estimated O & M is $2,649,065, and at the higher throughput the O & M cost drops to $15.69/Mg ($14.23/ton). In order to gain income from the sale of steam, the estimated $4,000,000 steam distribution system must be constructed. At 11-1/2 percent for 20 years, a normal rate of interest in Canada, the annual debt repayment on this new increment of construction would be $518,819, or $3.08/Mg ($2.79 per ton) of waste handled.

Funding of Investment--The investment in the facility of $8,900,000 was funded by the sale of debentures at varying interest rates and with periods of 10 and 20 years. Interest rates varied from 7-3/4 to 8-5/8 percent, with the average about 8-1/2 percent. The annual debt repayment for 1975 was $904,000. This is about an interest rate of 8-1/2 percent over a 20 year period.

Revenues--At the present time, the only revenue available is from the sale of recovered ferrous metal. The rate of recovery is running at about 4 percent and the market price is at $27.56/Mg ($25 per ton). On this basis, the ferrous metal revenue amounts to $1.10/Mg refuse ($1.00 per ton). This rate does not change with throughput.

The potential revenue from sale of steam would be tied to the probable cost of steam generation in customers' boilers, using fossil fuels and a comparison factor. Fossil fuels in Ontario presently cost about $1.48/GJ ($1.40 per million Btu) when purchased in quantity. Taking into account small boiler efficiencies, investment and other operating expenses, potential customers would certainly find their steam costs running close to $3.00 per 454 kg (1000 lb) (1.055 GJ or 1,000,000 Btu). A $2.75 figure will be used here for a conservative analysis, although a figure higher than this could be economically justified.

At the assumed $2.75 rate, this represents a potential gross revenue from steam sales of $21.79/Mg ($19.77 per ton) of waste.

The total possible revenue is:

Ferrous metal	$1.10	$1.00
Steam	21.79	19.77
TOTAL	$22.89/Mg Waste	$20.77/ton Waste

Each of the two boilers is rated at 272 Mg (300 tons) per day and 48 045 kg (105,700 lb) of steam per hour. If an 85 percent use factor is employed here, as before, then 0.907 Mg (one ton) of waste will produce 3267 kg (7,188 lb) of steam.

The total O & M cost therefore becomes $18.76/Mg ($17.02 per ton) of waste. This compares to a gross revenue of $22.89/Mg ($20.77 per ton) or a profit of $4.13/Mg (3.75 per ton).

If, for any reason, the plant does not reach the full 85 percent utilization suggested here, the O & M cost per ton will increase while the revenue per ton remains the same. The "break even" point is at a utilization of 138.353 Gg (152,522 tons) per year, or a factor of 69.6 percent.

SECTION 4

NASHVILLE THERMAL TRANSFER CORPORATION

INTRODUCTION AND SUMMARY

The Nashville Thermal Transfer Corporation, a "Not for Profit" Tennessee corporation, owns and operates a mass burning, refuse-fired incinerator in the city of Nashville that produces steam and chilled water for a district heating and cooling system for 30 buildings. The corporation, commonly referred to as THERMAL, has its offices and facilities at 110 First Avenue South, Nashville, Tennessee.

The facilities of THERMAL are located close to the downtown area of Nashville and for this reason have been designed as attractive, modern industrial buildings with extensive landscaping. There are two major structures, the refuse receiving--steam generator building and the water chiller building. Two boilers, each with a capacity of 327 Mg/d (360 TPD) of MSW, are used. Steam is produced at 323°C (613°F) and 2.86 MPa (400 psig). The chiller plant contains two 24.6 MW (7,000 ton) centrifugal chillers driven by steam turbines; the supply header operates at 5°C (41°F) and 1.34 MPa (180 psig).

Numerous combustion and air pollution problems have been experienced and modifications to the plant are now being completed.

CONCLUSIONS

- As with SWARU, essentially proven technology caused problems in the case of Nashville and redesign could remedy the situation. A refuse-fueled centralized heating/cooling system, particularly in a downtown area undergoing redevelopment, offers important costs savings for both the MSW disposal agency and clients for the air conditioning. This is accomplished because of minimum haul costs for collection vehicles to the waterwall incinerator compared to a landfill and the savings realized with one large steam/chilled water facility rather than a small one for each building.

- NTT originally recognized the advantages of the concept, and therefore it is unfortunate that a few initial problems compounded into a major financial situation. The critical problem was one not unique to waste processing facilities, but inherent in the low-bid requirements of governmental purchasing. When it became obvious that air quality standards could not be met with the wet scrubber system, cash flow projections could not be realized because of reduced capacity, increased fossil fuel costs, and customer dissatisfaction. Fire-side tubing problems then added to the conclusion that reorganization and refinancing was essential to the environmentally and economically sound operation of NTT. This was expeditiously managed and it is concluded that, with the addition of the two electrostatic precipitators and other improvements, the facility should be technologically acceptable. Conclusions cannot yet be made with regard to new economics. The zero drop charge plan originally employed by NTT leads to an unfair apportionment in operating costs, and it is recommended that such facilities accept revenues on the basis of the volume of refuse received.

- The lesson to be learned from Nashville is that a bargain in industrial equipment is a rarity. Estimated costs and revenues must be established by reliable and disinterested parties; a marginal design should never be considered acceptable.

PROCESS DESCRIPTION

The central heating and cooling plant of THERMAL uses a water wall, refuse-fired, mass burning incinerator similar to the steam-producing incinerator at Saugus, Massachusetts. The technology used is totally American rather than European and the requirements of a district heating and cooling system make the total installation considerably different from the Saugus operation. A simplified flow diagram of the THERMAL operation is shown in Figure 4. This process description and Figure 4 are based on the THERMAL facility as originally constructed; modifications are discussed in a following section.

Municipal refuse arrives at the incinerator plant in large trucks after being consolidated at distant transfer stations. The trucks discharge their load into a deep receiving pit and depart. There is no weighing of the loads because the original concept was to permit no-charge dumping at the plant and close down the receiving operation each day when sufficient refuse was on hand. Refuse in the pit is mixed and dumped into the charging chutes of two 327 Mg/d (360 TPD) mass burning boilers by two overhead travelling cranes, one of which is normally a standby.

Refuse in the charging chute drops by gravity to a four-section Detroit Reciprocating Grate Stoker. The first section is the charging grate section, the second and third sections accomplish drying and burning, and the fourth section completes the burnout. Ash from the last section drops into a hopper, is quenched with water, and finally drops from the hopper into a truck for disposal. The ash that drops through the grates is removed by a separate system, with two chutes dumping into the same truck. These siftings are not quenched.

Hot gases from the burning refuse pass through a superheater tube bank, a boiler generating tube bank, and an economizer in a single pass, and then exit to a cyclone-type dust collector. The heavy particles extracted from the flue gas are returned to the ash hopper. The flue gas from the cyclone collector originally passed through a low energy wet scrubber before exiting to the atmosphere through an induced draft fan (not shown) and stack. Primary

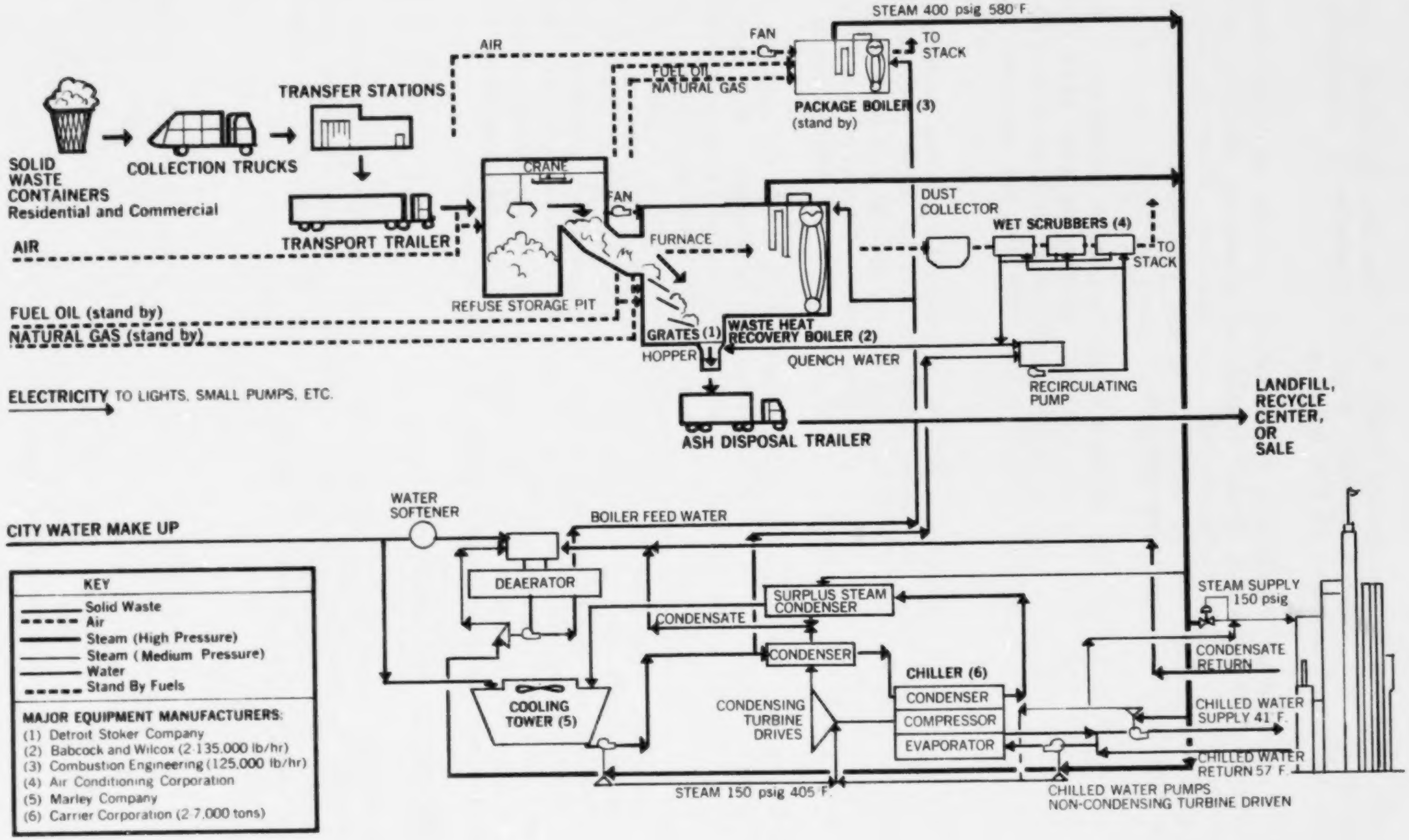
SOLID WASTE CONTAINERS Residential and Commercial
COLLECTION TRUCKS
TRANSFER STATIONS
TRANSPORT TRAILER
AIR
FUEL OIL (stand by)
NATURAL GAS (stand by)
ELECTRICITY TO LIGHTS, SMALL PUMPS, ETC.
CRANE
REFUSE STORAGE PIT
FAN
FURNACE
GRATES (1)
HOPPER
WASTE HEAT RECOVERY BOILER (2)
QUENCH WATER
ASH DISPOSAL TRAILER
LANDFILL, RECYCLE CENTER, OR SALE
AIR
FAN
FUEL OIL
NATURAL GAS
PACKAGE BOILER (3) (stand by)
TO STACK
STEAM 400 psig 580 F
DUST COLLECTOR
WET SCRUBBERS (4)
TO STACK
RECIRCULATING PUMP
CITY WATER MAKE UP
WATER SOFTENER
BOILER FEED WATER
DEAERATOR
CONDENSATE
SURPLUS STEAM CONDENSER
CONDENSER
CHILLER (6)
CONDENSER
COMPRESSOR
EVAPORATOR
CONDENSING TURBINE DRIVES
COOLING TOWER (5)
STEAM 150 psig 405 F
STEAM SUPPLY 150 psig
CONDENSATE RETURN
CHILLED WATER SUPPLY 41 F
CHILLED WATER RETURN 57 F
CHILLED WATER PUMPS NON-CONDENSING TURBINE DRIVEN
KEY
Solid Waste
Air
Steam (High Pressure)
Steam (Medium Pressure)
Water
Stand By Fuels
MAJOR EQUIPMENT MANUFACTURERS:
(1) Detroit Stoker Company
(2) Babcock and Wilcox (2-135,000 lb/hr)
(3) Combustion Engineering (125,000 lb/hr)
(4) Air Conditioning Corporation
(5) Marley Company
(6) Carrier Corporation (2-7,000 tons)

Figure 4. Flow diagram of the Nashville Thermal Transfer Corporation.

combustion air is drawn by the forced draft fans from the refuse pit area, thereby keeping the pit under a constant negative pressure to reportedly trap and eliminate odoriferous gases in the boilers.

In order to maintain dependable steam output, and for peaking, there is a standby oil/gas-fired package boiler capable of producing slightly more steam than one of the refuse-fired boilers. In addition, there is provision to fire each of the refuse boilers with oil or gas to stabilize combustion and increase dependability of steam service.

Steam produced by all of the boilers enters a common header at 2.86 MPa (400 psig) and 325°C (620°F). For the district heating system, this steam is reduced to 1.14 MPa (150 psig) by non-condensing steam turbine drives which operate between the two pressures. These steam turbines are used for plant auxiliaries.

The centrifugal compressors are driven by condensing steam turbines using the 1.14 MPa (150 psig) steam exhausted from the chilled water pump drives and cooling tower pump drive. There is always some demand for both chilled water and steam throughout the year. The plant makes extensive use of steam drives for most auxiliary equipment as well as the chilled water system.

All of the energy derived from refuse in this facility is used for district heating and cooling in 30 downtown Nashville buildings. In order to accomplish this, it was necessary to install steam distribution and condensate return pipelines, and supply and return chilled water pipelines. Steam is distributed at 1.14 MPa (150 psig) and condensate return is pumped at low pressure. Steam use is metered at each branch line to customers' premises. The chilled water supply header operates at 1.34 MPa (180 psig) and 5°C (41°F), with the return operating on residual pressure from customer systems and a design temperature of 14°C (57°F). The chilled water lines are uninsulated. Some customer systems use the pressure difference between the chilled water supply and return lines for their own internal circulation, while others use more sophisticated pumped and valved systems.

EQUIPMENT DESCRIPTION AND OPERATION

The successful operation of any processing plant, especially of one that processes refuse, depends heavily on the performance of the equipment, as well as on the workability of the flow design. Some of the key items of equipment, and their performance, are described below.

Boilers

The mass-burning boilers are waterwalled units manufactured by Babcock and Wilcox. There are two boilers, each with a rating of 327 Mg/d (360 TPD) of municipal refuse while producing a steam output of 49 442 kg/h (109,000 lb/hr). Design steam conditions are 2.86 MPa (400 psig) at 323°C (613°F) from 116°C (240°F) feedwater. The boiler design pressure rating is 3.55 MPa (500 psig). The outlet gas temperature averages 221°C (430°F).

The grate system is a four-section Detroit Reciprocating Grate Stoker. The second section receives the refuse from the charging chute "first section," and begins to dry it by exposure to the hot atmosphere of the furnace. Actually, much of the refuse ignites and begins to burn on this second grate. The primary combustion takes place after the refuse has tumbled from the first to the second grate, and the final burnout occurs on the fourth grate.

The primary function of the underfire air being blown up through the grate sections is to provide sufficient oxygen for combustion and its secondary purpose is to keep the grate temperature within the operating limits of the metal grate material. Overfire air is blown into the furnace through the front and rear wall air jets. Three 10 cm (4 in.) side wall air jets were installed on each side wall of the boilers, with the air coming from the overfire fans, in an attempt to control the corrosive reducing atmosphere that normally occurs near the level of the burning refuse. This attempt to control the reducing atmosphere worked to some degree, but both furnaces have been modified by the addition of silicon carbide refractory protection from the grate level to a height of 6.1 m (20 ft) on the sidewall tubes. This is a feature that the furnaces at Saugus, Massachusetts, had from the beginning. At present, the No. 2 furnace side walls are being metallized with a 0.38 mm (0.015-in.) coat of aluminum. This begins at the top of the silicon carbide and extends to 1.2 m (4 ft) below the roof tubes.

During the first few months of operations, the plant operators attempted to use variation of both underfire air and overfire air to control steam output rather than to adjust air flow to the required boiler conditions. This is considered to be one of the contributing factors to boiler tube corrosion and possible damage to the superheaters. The problem has been resolved, as part of a new capital completion program, by replacing the superheaters with new, larger units, with heavier gauge tubes. It remains difficult, however, to maintain draft on the boilers with the installed turbine-driven induced draft fans.

A performance test of one of the boilers by the manufacturer was conducted from February 10, 1975, to February 27, 1975. Some of the important averaged test results are tabulated below:

	Measured Value	
Parameter	SI	English
Load (98% Capacity)	48 535 kg/h	107,000 lb/hr
Refuse Rate	13.7 Mg/h	15.1 TPH
Steam Temperature	301°C	573°F
Feedwater Temperature	112°C	233°F
Outlet Gas Temperature	221°C	430°F
Refuse Higher Heating Value	11.34 MJ/kg	4875 Btu/lb

Parameter	Measured Value SI	Measured Value English
Boiler Efficiency	71.9%	71.9%
Refuse Weight Reduction	78.3%	78.3%
Refuse Volume Reduction	92.3%	92.3%
Total Loss of Combustibles	2.3%	2.3%
Putrescibles in Ash	0.072%	0.072%
Outlet Particulate Loading at 12% CO_2	3.17 g/Nm^3	1.46 grains/SDCF

In addition to the above tabulated test results, the parts of the report dealing with flue gas analysis and the particulate size distribution are of interest. These are tabulated below:

FLUE GAS ANALYSIS

CO_2	10.4 vol-%
O_2	9.5 vol-%
Excess Air	84 vol-%
NO_x	146 ppm
SO_2	38 ppm
CO	153 ppm
Chloride	110 ppm

FLY ASH PARTICLE SIZE DISTRIBUTION

	Particle Size, μm (Percentage less than stated size)			
Test Date	10	5	1	0.3
2-21-75	56%	40%	32%	22%
2-21-75	32%	22%	19%	16%
2-23-75	44%	32%	24%	14%
2-26-75	26%	18%	14%	11%
2-26-75	38%	28%	18%	10%

These tests were conducted under controlled conditions and with all equipment pre-tested and properly adjusted. As such, the reported performance, especially boiler efficiency, probably represents the maximum to be expected from this particular installation. Another factor that strongly affects the results of the boiler tests is that the fossil-fueled "stand-by" boiler was also operating at the same time to furnish enough steam to meet the demand and to smooth out steam output. Therefore, the large uncontrollable swings in steam pressure and temperature that are typical of mass-fired boilers did not occur in the test.

Boiler Controls

There are both pneumatic and electrical components in the boiler control system. In this respect, the controls are the usual systems associated with grate-fired boilers, and, if they are used as designed, they will function well. Matching the boiler output to steam demand, except for very slow and gross changes, has not proven possible. This is inherent to the type of fuel used and the grates employed.

The only abnormal features of the control systems are the use of air, filtered and dried, from the plant compressed air system for the pneumatic controls and the direct connection of electrical controls to the plant electrical system. Both of these features are attempts to reduce capital investment by omitting desirable redundant equipment. The results have been poor. When the plant air system is being used to run tools for maintenance and repair, the system air pressure sometimes drops low enough to affect the pneumatic boiler controls, and the result is an unscheduled shutdown. At present there is only one primary feeder line to the plant, and occasionally the plant is affected by a power outage. Both of these conditions will be corrected during the capital completion program.

Air Pollution Control Equipment

The failure of the pollution control equipment at THERMAL to meet local, state, and federal emission standards has been as serious a problem as the boiler tube design one. The original pollution control equipment on each boiler consisted of a multi-cyclone dust collector for the large particles and a low energy horizontal wet scrubber. Even after attempts to improve and modify the operation, the lowest emission level that could be attained was 0.365 g/Nm^3 (0.168 grains/DSCF), a little more than double the allowable maximum of 0.173 g/Nm^3 (0.08 grains/DSCF). After extensive investigations, THERMAL concluded that for its particular operation, only an electrostatic precipitator could produce the desired results.

Possible cause for poor scrubber performance may be found by comparing the scrubber design specification to the particle size distribution reported in the Babcock and Wilcox boiler performance test results. The scrubbers were specified to remove 95% of all particulate matter based upon a 5 μm mean particle diameter. The particle size data indicated that up to 40% of the particles were under 5 μm and that the average distribution of such particles was 28%. Furthermore, these same tests show an average particulate size distribution of 21.4% under 1.0 μm and 14.6% under 0.3 μm. The large percentage of particulates in the sub-micrometre range, which is difficult to scrub out, may be one explanation for the problems encountered. The flue gas, in combining with the scrubber water, created a very active acidic condition that rapidly corroded the scrubber's internal parts and casing.

THERMAL purchased one electrostatic precipitator that had to be installed, checked out, and in operation by October 29, 1976, to meet the requirements of a Compliance Order of the EPA. The specifications indicate a guaranteed outlet loading of 0.032 g/Nm^3 (0.015 grains/DSCF) (adjusted to 12% CO_2) with an inlet loading of 100 times that level. This unit should satisfy the air pollution control requirements on one boiler. Installation of an identical precipitator on the second boiler began about October 1, 1976.

Water Chillers

The water chiller plant contains two 24.6 MW (7,000 ton) centrifugal chillers driven by steam turbines. They are equipped with variable inlet vanes, which, in conjunction with turbine speed control, permit a variation in chiller output from the maximum down to as low as 2.46 MW (700 tons), a 10-1 output adjustment ratio. The operators of the plant report that this output adjustment ratio is sufficient for their needs.

Initially, one of the chillers experienced excessive vibration, which limited its use for some time. The trouble was traced to the governor valve stem, which was replaced, and the same modification was made to the second chiller.

Steam Turbine Drives

The entire plant was designed to make maximum use of steam turbine drives on auxiliary equipment. Specific exceptions of this are the forced draft fans and two 0.014 m^3/s (240 GPM) boiler feed pumps driven by electric motors. This design approach was taken to reduce the need for expensive electric power. The operators of the plant have indicated that they would not choose steam turbine drives for auxiliaries again. The major reason would appear to be a lack of operating flexibility and dependability. Turbine performance varies considerably with steam pressure, and this may vary over a wide range in a mass burning boiler. One of the high pressure chilled water distribution pump drives has already been replaced with an electric motor, and when the new precipitators are installed, the installation will include new induced draft fans with electric motor drive.

Most of the turbines on auxiliaries use steam at 2.86 MPa (400 psig) and 316°C (600°F) and exhaust at 1.13 MPa (150 psig). The exhaust steam is used for the two centrifugal water chiller drives and for distribution into the district heating system.

Materials Recovery

At present there is no provision for recovery of material resources. The plant design is consistent with the fact that mass burning incineration leaves little of practical value to be recovered from the ash, except for the magnetic metals. With the original intent being to generate steam at minimum costs, no provisions for recovery of the ferrous fraction was made in the design. This leaves 6% by volume of the original refuse to be landfilled.

Refuse Supply

The refuse is delivered to the facility by Metropolitan Nashville (METRO) in transfer trucks. Bulky waste, heavy items, and large incombustibles are supposed to be separated from the waste before delivery, but there is provision, via by-pass chute, for the cranes to set aside any such items that arrive. METRO does not pay any drop charge per ton, but does provide an annual payment for services. Title to the refuse is retained by METRO throughout the operation. This would be a complicating factor if materials recovery were attempted.

Studies have indicated that there is a more than adequate supply of refuse to keep the plant in operation and provide for future expansion. In that the plant is sized to accept only a part of Nashville's refuse, it is possible to schedule receipt of refuse to suit the steam demand. This eliminates the necessity for adjustment of refuse supply to steam demand or vice versa, a problem faced by most refuse-to-steam energy recovery facilities.

Distribution Piping

The steam and chilled water distribution piping is located in a common trench with other utilities that were installed at the time. Only the steam supply line is insulated, with an insulation barrier being placed between the steam and chilled water lines when the pipes were installed.

The steam supply line is steel, insulated with calcium silicate, and installed in a prefabricated steel conduit. The chilled water lines are of ductile iron with an "Enameline" cement lining, and assembled with mechanical joints.

At present there is only one distribution network, but there is provision for addition of a second network or extension of the existing system as new customer areas are developed. All piping is sized for future expansion.

ENGINEERING EVALUATION

This facility was designed, built, and placed in operation with a minimal expenditure of funds. Outwardly, the incinerator plant is very similar to the plant operated by RESCO at Saugus, Massachusetts, and many European installations, but economic considerations forced the designers to take a much less conservative approach. The result is that the RESCO plant has performed well from the beginning, while THERMAL's plant has had a multiple of start-up problems. Most of the problems and their solutions have been discussed and the capital completion program is intended to provide those solutions. When these problem areas are cleared up, there should be a considerable improvement in overall operational dependability and economics. In fact, the modifications completed thus far have steadily improved plant performance, so much so, that steam deliveries for 1976 increased 57% over 1975, and chilled water deliveries increased 112%.

Boilers

The boiler tests for February 10 to 27, 1975, developed some useful information such as flue gas analysis and particle size distribution. The boiler performance data, however, is suspect, because of the operation of a fossil fueled boiler in parallel with it during the test.

The THERMAL operating staff reports that these mass burning boilers may experience a mostly uncontrollable swing in output of 6 804 kg/h (15,000 lb/hr) above and below the working level, and that a 6 804 to 9 072 kg/h (15,000 to 20,000 lb/hr) change may occur over a 10 minute time period. With a relatively constant demand for steam, these violent swings in output can only be accommodated by exhausting or condensing excess steam when the swing is high and making more steam with fossil fuel when the swing is on the low side. Either situation is costly and plant economics suffer. Good performance of the grate and charging chute to maintain close control of refuse fed to the boiler can help to reduce the amount of swing, but cannot eliminate it. It is reported that the existing grate and chute combination does not afford the needed close control of refuse feed.

Grates

The THERMAL operating staff reports that the grates jam occasionally. It is their opinion that the grate support arrangements appear to be inadequately sized for the amount of weight they have to support when the material is wet. These grates are essentially identical to those that would be used to fire coal and it is apparent that some modification is necessary to adapt them to firing unprocessed refuse.

Load Matching

THERMAL's refuse-to-energy operation is the first attempt in the United States to convert refuse to steam destined solely for a district heating and cooling system. Such an operation is an exceedingly difficult one to control for profitable operation. There are three major variables that are basically uncontrollable, but must be accommodated in the overall system. These are:

Refuse Supply

Usually, when a waste handling facility is constructed, it is planned to handle all of the waste from a nearby geographical area. The volume of waste generated in such a service area will vary daily and by season, according to the habits of the people in the area, and not be generated in relation to the needs of the plant. THERMAL has avoided this variable by providing a disposal service for only a part of the refuse generated in Metropolitan Nashville. Delivery of refuse to the plant can be scheduled within certain limits.

Boiler Performance

The output of a refuse-fired boiler depends on the heating value of the refuse and its moisture content, both of which may vary greatly in a very short time. In mass burning boilers, such as those at Nashville, the swings in output are very wide. In addition, the response of a mass burning boiler to changes in firing rate is very slow. For these reasons, a mass burning refuse-fired boiler cannot be used under conditions where it must vary output quickly to match the steam system load changes. It is claimed that pre-preparation of the refuse fuel by shredding and then firing it in a somewhat differently designed boiler can result in the controlled variable output needed. Though this seems reasonable, it has not been proven in an actual installation.

Load Variation

The steam load imposed on a producing plant by a district heating and cooling system will vary according to time of day and season. Sometimes the daily load variations occur quite rapidly. THERMAL reports that there is some demand for both steam and chilled water throughout the year, indicating extensive use of blending type air conditioning systems and/or a need for dehumidification. This tends to smooth out the load fluctuations, but certainly does not eliminate them. The periods of lowest demand are spring and fall. THERMAL has no major industrial customers whose demand might be used to smooth out the total load fluctuation on the plant.

A mass burning boiler installation such as Nashville's must have the additional capability of burning gas or oil, either along with the refuse or in a separate standby boiler. Both options may be required in order to meet the steam demand when the heat content is low, or moisture level of the refuse is high, and to adjust system output to demand on rapid changes. This expense for fossil fuel is not always considered in project planning.

Conversely, when steam output is momentarily high because of high heat content or low moisture of the refuse fuel, there must be some means of condensing excess steam. Without a means of recycling the excess steam into the treated water system, it must be blown off to the atmosphere. This represents the dual loss of both energy and of treated water used to make the steam. THERMAL has an excess steam condenser but it does not seem to be large enough.

The low total load condition experienced in any district heating and cooling system in spring and fall results in inefficient use of the total capital investment in the plant during that period. This is another reason for attempting to build up a diversified load structure, to make the average demand more nearly approximate the maximum demand.

Table 1 shows energy sales and fuel usage from June, 1974, through July, 1976. In calendar year 1975, THERMAL incinerated 73.177 Gg* (80,662 tons), 61% of the total capacity of one boiler system. In the first seven months

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* All refuse weights reported here are based on periodic calibration of quantity held within the grapple bucket.

TABLE 1. COMPARISON OF ENERGY SALES VERSUS FUEL CONSUMPTION

Month/Year	Energy Sales		Fuel Used		
	Steam, lb	Cooling, ton-hrs	Solid Waste, ton	Gas, $10^2 ft^3$	Oil, gal
June 1974	1,596,000	198,890	163	600,300	0
July	6,582,000	298,906	0	690,000	0
August	3,383,000	325,066	595	923,600	0
September	7,234,000	530,722	3,257	880,300	96,300
October	12,432,000	557,414	7,693	0	444,200
November	15,198,000	382,213	6,813	0	353,340
December	17,132,000	435,297	8,190	220,000	137,800
January 1975	13,452,000	407,359	7,286	75,568	105,807
February	23,276,000	422,336	6,554	207,424	91,606
March	17,523,000	999,188	9,401	193,100	6,150
April	24,783,000	550,786	6,925	259,118	58,206
May	8,981,000	1,561,713	333	686,700	0
June	6,224,000	2,806,212	1,054	556,900	0
July	5,689,000	2,314,840	7,962	88,984	0
August	5,261,000	2,427,387	6,610	34,600	0
September	12,223,000	2,240,076	7,328	23,300	28,350
October	17,543,000	1,775,614	8,721	83,070	27,142
November	27,518,000	1,193,921	8,827	96,106	32,573
December	37,670,000	709,797	9,661	61	111,944
January 1976	40,552,000	623,280	10,557	90	115,296
February	28,378,000	965,595	7,302	132,728	141,596
March	27,334,000	1,396,590	7,229	143,100	0
April	14,963,000	1,335,335	7,200	20,087	0
May	14,060,000	1,695,765	8,379	134,700	0
June	8,147,000	2,385,914	6,811	243,200	0
July	7,723,000	2,498,861	6,500	282,600	0
	404,830,000	31,039,077	161,351	6,575,636	1,750,310
	(183.63 Gg)	(28,158,650 Mg-h)	(146.38 Gg)	($18.615 \times 10^6 m^3$)	($6.624 \times 10^3 m^3$)

of 1976, THERMAL operated at 71% capacity, and reportedly are near 100% (one boiler) by April 1977. The total operating experience with regard to fuel usage is summarized as follows:

Fuel	Percent of Total	Amount Used		Heating Value		Oil Equivalence	
		SI Units	English Units	TJ	10^9 Btu	$10^3 m^3$	Barrels
Oil	8.5	6.624×10^3 m^3	1,750,310 gal	258.520	245.043	6.624	41,674
Gas	23.5	18.615×10^6 m^3	657.564×10^6 ft^3	711.141	674.003	18.219	114,626
Wastes	68.0	146.38 Gg	161,351 tons	2 042.911	1,936.212	52.340	329,288
Total						77.183	485,588

Steam Driven Auxiliaries

The extensive use of steam auxiliaries, as at Nashville, may result in some saving in operating cost, but there is a considerable sacrifice in operating flexibility. Auxiliaries that require high starting and running torque or very low speed should not be planned for steam turbine drive at all. When nearly all auxiliaries are steam driven, it is necessary to have an auxiliary or standby boiler that is equipped with electric auxiliaries in order to build up steam to fire up the main boilers. Since a standby is needed anyway, this is not a serious problem, but considerable time is required to bring a boiler that is using steam-driven auxiliaries up to pressure. During this start-up period, there is a much greater probability of excessive particulate emissions, and a plant that at other times meets all air quality standards may be cited for a violation.

Steam turbine performance is sensitive to steam inlet conditions. If steam pressure falls due to variation in the heating value or moisture content of the refuse, the performance of important turbine drives may be so seriously affected that a boiler malfunction or shutdown will occur. This has happened at Nashville several times.

Air Pollution Control

The problems with the wet scrubbers and the subsequent correction by the addition of electrostatic precipitators have already been discussed. The original tests in September, 1976, of the first precipitator demonstrated that solid particulate values below 0.07 g/Nm^3 (0.03 grains/SCF) at 12% CO_2 were being achieved. Retest in March, 1977, indicate that stack effluent is in the range of 0.017 to 0.019 g/Nm^3 (0.007 to 0.008 grains/SCF), an efficiency greater than 99.5%. What must be made clear, however, is that no air pollution control equipment of any type can be expected to perform satisfactorily unless its design is based on a knowledge of the performance of the furnace. The output flue gas conditions must be known as they actually occur with the fuel used in the furnace. The flue gas measurements taken by Babcock and Wilcox as part of their tests are valuable in this regard, but the flue gas conditions from an actual shredded waste fired furnace, such as at Hamilton, Ontario, are still unknown because no such tests have ever been made. Also the flue gas conditions from a Von Roll type mass burning furnace are not generally known because such installations are proprietary and the data are normally not made available.

PROJECT DEVELOPMENT

The Nashville Thermal Transfer Corporation was the product of a late 1960's drive for urban renewal in downtown Nashville. In response to the city's needs, Mayor Beverly Briley commissioned a study to determine the feasibility of a district heating and cooling facility for public and private buildings. The study indicated that such a facility to serve the central city was practical, and city officials decided to proceed, based on a time table that called for construction to start in 1972 and for completion in 1974. In order to undertake such a sizeable job on a tight schedule, Nashville Thermal Transfer Corporation, a "Not for Profit" corporation, was established. THERMAL was initially created as the developer and operator of a district heating and cooling system.

In 1970, about the time THERMAL was organized, it was suggested that the required steam be produced by burning the refuse from the city, thereby solving a part of that problem also. Accordingly, a second study that established the feasibility of deriving energy from refuse was commissioned. THERMAL then became a refuse disposal organization as well as the operator of a district heating and cooling system.

The main objectives of the new facility were:

- Provide low cost district heating and cooling for center city buildings.
- Recover energy in all combustible solid waste not recycled for other purposes.
- Partially eliminate the need for sanitary landfill.
- Substantially reduce the cost of solid waste disposal.
- Improve water and air quality in urban Nashville by meeting solid waste disposal, water pollution, and air emission standards with a central plant that incorporates effective environmental control equipment.
- Provide for major ferrous metal recycling from incinerator residue.
- Create and operate a solid waste-fueled central heating and cooling plant project that has a favorable economic and environmental impact on the community.

The project has thus far met many of the stated objectives, and, with the improvements that are now in progress, should substantially meet all of them. A review of each objective and of the plant's history to date indicates:

- Low cost heating and cooling - This objective has not been attained. Delivered prices for steam and chilled water are presently higher than the equivalent energy charge from the local power company or for purchase of fossil fuel. However, if each customer were to add the amortized cost of his investment in refrigeration equipment and boilers to these supposedly low energy costs, the total comparable energy cost would more nearly approximate the cost of services from THERMAL. In addition, the improvement in plant performance and increased output expected from the ongoing modifications should reduce the cost of heating and cooling services supplied by THERMAL while prices for fossil fuel and electric power are steadily rising.

- Recover energy from solid waste - This objective was successfully reached as soon as the plant operated its refuse boilers and sold the steam product to customers. As the operation improves, this conversion will be more efficient and reach a greater total.

- Partially eliminate the need for sanitary landfill - Every unit volume of refuse burned in this plant is at least 0.9 of a unit that does not have to be landfilled. As the plant operation improves and ultimately approaches its design capacity, the refuse burned (up to 653 Mg or 720 tons per day) becomes the equivalent of a substantial landfill operation.

- Substantially reduce the cost of solid waste disposal - The plant certainly has done this for Metropolitan Nashville. In the beginning, Nashville guaranteed to deliver waste to the plant "at no cost." This meant no cost to THERMAL but also resulted in "no cost" to Nashville. Later, Nashville contributed up to $150,000 per year to the operation to pay for services rendered. The plant does not weigh refuse as received, so there is no positive record of the number of tons of refuse burned; but a review of steam and chilled water sales for fiscal 1975, just after start-up, indicates a total for the year of about 39 Gg (43,000 tons) and the same sort of review for fiscal 1976 indicates a total consumption of about 72.6 Gg (80,000 tons). The payment of $150,000 per year seems to be equivalent to a drop charge of $3.85/Mg ($3.49 per ton) in fiscal 1975, normal for many cities in the United States. In fiscal 1976 this figure drops to $2.06/Mg (1.87 per ton), a very low figure. There is some indication that Nashville might substantially increase the payment to THERMAL.

- Improve water and air quality in urban Nashville - This objective has been reached in spite of the poor performance of the wet scrubbers. If each of THERMAL's customers were to be individually and privately heated, the total emissions would be greater than now produced by the Nashville refuse disposal plant. Here, the efficiency of large size and added control equipment makes the difference.

- Provide for major ferrous metal recycling from residue - This objective has not been attained or even attempted. There is no reason why equipment for ferrous metal recovery cannot be added to the plant if pricing on the metal salvage market indicates that it would be economically feasible.

- Create a favorable economic and environmental impact on the community - This objective has been partially attained in improvement of the environment and in economic benefit to the City. The development of reasonable rates for steam and chilled water while assuring amortization of investment is an objective within reach but not yet attained. The organization of THERMAL and the construction of its existing facilities were financed by the issuance of $16,500,000 worth of revenue bonds, the last of which will mature in June, 2002. When all bonded indebtedness has been repaid, the facilities will become the property of Metropolitan Nashville.

FINANCIAL ANALYSIS

In October, 1975, R. W. Beck and Associates issued a feasibility report that resulted from their analyses, investigations, and studies of the THERMAL proposal to obtain additional financing. This was a comprehensive study of all aspects of continued operation of THERMAL. The study generally agreed with the findings of the Management and their Consultant as to the modifications and improvements required to make the plant efficient and dependable. The cost estimated for needed modifications and improvements, combined with paying off short term loans and some unpaid construction debts, were found to require an issue of junior lien bonds to an amount of $9,250,000.

The total projected revenues for 1976, based on existing steam and chilled water rates with no additional customers, was $3,267,000. Without labor and fuel costs, this total annual revenue increases to $5,096,000 by 1985. Because present rates are in excess of the rate formula originally written into customer contracts, there is a delay period built into the rate increase mentioned above to allow normal inflation to "catch up" with the established rate.

On the assumption that the $9,250,000 bond issue would become a reality and the further assumption that the METRO Council would pass an ordinance increasing the payment of $1,500,000 per year, a pro-forma income statement was prepared, again on the basis of existing customers only. The income statement shows that THERMAL can meet the needs of adequate service without using all of the $1,500,000 per year guarantee from METRO. The actual projected need for METRO funds ranges from $986,000 in 1976 to $1,407,000 in 1979, with the ten year average between 1976 and 1985 at $1,258,200. If the average payment were expressed as a disposal fee, it would amount to a disposal fee of $6.59/Mg ($5.98 per ton) when the plant is operating at 80% of capacity, a reasonable level. However, if the refuse consumption of the plant remains relatively low, equivalent to the steam and chilled water demand, this equivalent disposal fee would more than double.

If additional customers are added to the system, which is possible at nominal increase in operating cost, the projected net increase in revenues available for debt service will reduce the METRO average ten year payments to $1,026,800 per year, or an equivalent disposal fee of $5.38/Mg ($4.88 per ton), a very reasonable figure.

THERMAL management has chosen a different method of financing to obtain the needed extra funds. Their present plans are to secure a loan of $5,700,000 for construction of environmental protection facilities, which will be guaranteed by the State of Tennessee, and bank loans totaling $2,300,000, for a total of $8,000,000. This total is somewhat less than the need indicated by the R. W. Beck report, but the loss will be partially offset by the elimination of bond issue costs and the necessity of capitalizing the Debt Reserve Fund.

Funds for the modifications programs presently underway to comply with EPA orders have been provided by short-term loans from local banks. Loan terms and interest rates are under negotiation at present; therefore no specific statement can be made on expected net revenues. With the reduced loan amount, however, it should be feasible to stay within the projections made by R. W. Beck even if interest rates are somewhat higher than those of a bond issue.

LITERATURE

References 2 through 5 contain much of the published information on the development and operation of THERMAL.

SECTION 5

CITY OF CHICAGO-COMMONWEALTH EDISON SUPPLEMENTARY FUEL SYSTEM

INTRODUCTION AND SUMMARY

The City of Chicago Supplementary Fuel Processing Plant is undergoing start-up testing in the spring of 1977. It is patterned after the City of St. Louis/Union Electric Company demonstration system that has been operating during the past four years. The facility processes MSW to make refuse-derived fuel (RDF), which is then co-fired with coal in the steam generators of a large electric power generating station. Depending on maintenance experience, the plant has a capacity of 2250 to 2866 Mg refuse per day (2,480 to 3,160 TPD) and can produce 1566 to 1996 Mg/d (1,726 to 2,200 TPD) of RDF.

The City of Chicago does not have adequate landfill sites within its borders to handle its solid waste disposal requirements. It has traditionally relied on city owned and operated mass burning incinerators to dispose of city-collected refuse, which averaged 20.9 Gg (23,000 tons) per week in 1972. Concerns with replacing aging units in its existing incineration facilities and upgrading other units to meet EPA air emission standards led the city to undertake an exhaustive study in late 1972 to determine what the next increment of disposal facility should be. Because construction and operating costs were escalating to new highs, the study criteria included a survey of disposal technology to determine which system would best satisfy the city's requirements. The study found, based on economics, technological effectiveness, and sociopolitical considerations, that the St. Louis/Union Electric system best satisfied these requirements. The city then authorized the design and construction of an RDF facility and negotiated an arrangement to sell RDF to the Commonwealth Edison Company, which would burn it along with coal in the power boilers of its Crawford Station.

The information presented here has been entirely obtained from records of the City of Chicago and The Ralph M. Parsons Company. The only published article with any level of detail is that of Zralek and Bailey (Ref. 6).

CONCLUSIONS

- Although the waterwall refuse combustion system is considered the most technologically established waste-to-energy process, use of a refuse-derived fuel to partially supplement coal in existing furnaces is expected to become increasingly popular because of first-cost considerations. The RDF is sold strictly on the basis of its value as a fuel to a customer already owning the steam generator-ash handling-emission control system; hence, the high capital cost associated with this portion of the equipment need not be borne by the waste processing organization. This organization becomes a fuel seller rather than an energy processor-consumer.

- The mechanical processing required to yield the RDF, and which simultaneously results in an inorganic-rich fraction, is expected to provide the impetus for further R&D on commercial recovery of other materials. If the selling price of the RDF and ferrous metals will cover the costs for the initial particle size reduction and air classification, then sufficiently economical methods for isolation of several non-ferrous metals and glass might be realized. Purity of the fractions now obtained is rather low and it is recommended that research be continued to achieve a higher degree of component separation.

- The Chicago plant is just now undergoing startup testing. The first 6 to 12 months of operation should reveal information on the performance of individual equipment and subsystems. Hopefully, the owner will share this experience so that new plants will benefit from previous observations.

PROCESS DESCRIPTION

Flow Diagram

The primary purpose of a refuse-derived fuel (or supplementary solid fuel) plant is to process the combustible fraction of raw refuse into a transportable fuel for use typically in a coal-fired, suspension-burning boiler at a large power plant. The requirement for the fuel for Chicago is that the particles be approximately 3.8 cm (1-1/2 in.) in size, and light enough to permit good burnout in suspension burning.

Figure 5 shows the process flow diagram for each train of processing equipment. Key pieces of equipment at the fuel processing plant and at the power generating plant are indicated; also shown are the quantities of materials handled at various points in the system. The raw refuse is delivered to the tipping floor at a nominal rate of 72 Mg/h (80 TPH). It is pushed into the coarse or primary shredder feed conveyor by means of a front loader and the coarse shredder then reduces the material to particles that have a maximum dimension of 20.3 cm (8 in.). These particles travel by conveyor into an air classifier that separates the material into light and heavy fractions. The light fraction is composed mainly of combustibles, which are readily airborne. The heavy fraction contains the non-combustible items and those heavy particles of combustible materials that do not readily burn in a suspension-fired system. This heavy fraction is conveyed to storage bins for eventual disposal. On the way to the bins, the stream is passed under a magnetic separator that diverts the ferrous material into one storage bin, while the remainder goes to another. Aluminum is not recovered because waste samples indicated insufficient quantities for economical recycling.

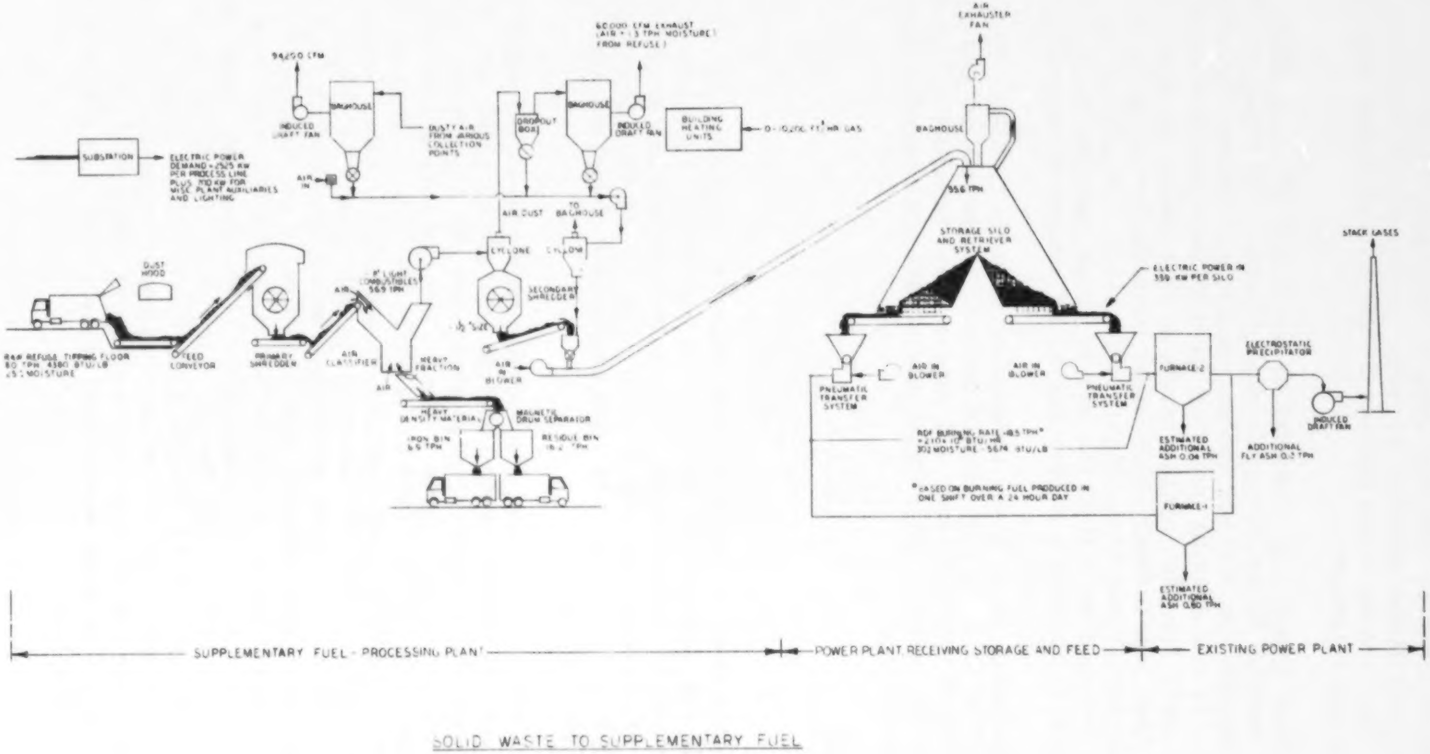

94250 CFM
INDUCED DRAFT FAN
BAGHOUSE
DUSTY AIR FROM VARIOUS COLLECTION POINTS
AIR IN
SUBSTATION
ELECTRIC POWER DEMAND = 2525 KW PER PROCESS LINE PLUS 710 KW FOR MISC PLANT AUXILIARIES AND LIGHTING
60,000 CFM EXHAUST (AIR + 1.3 TPH MOISTURE FROM REFUSE)
DROPOUT BOX
BAGHOUSE
INDUCED DRAFT FAN
BUILDING HEATING UNITS
0 - 10,200 FT³/HR GAS
AIR DUST
TO BAGHOUSE
CYCLONE
CYCLONE
SECONDARY SHREDDER
-1½" SIZE
DUST HOOD
RAW REFUSE TIPPING FLOOR 80 TPH 4380 BTU/LB 25% MOISTURE
FEED CONVEYOR
PRIMARY SHREDDER
AIR
8" LIGHT COMBUSTIBLES 56.9 TPH
AIR CLASSIFIER
HEAVY FRACTION
AIR
AIR IN BLOWER
HEAVY DENSITY MATERIAL
MAGNETIC DRUM SEPARATOR
IRON BIN 6.5 TPH
RESIDUE BIN 16.2 TPH
AIR EXHAUSTER FAN
BAGHOUSE
55.6 TPH
STORAGE SILO AND RETRIEVER SYSTEM
ELECTRIC POWER IN 350 KW PER SILO
AIR IN BLOWER
AIR IN BLOWER
PNEUMATIC TRANSFER SYSTEM
PNEUMATIC TRANSFER SYSTEM
RDF BURNING RATE = 18.5 TPH* = 210 × 10⁶ BTU/HR 30% MOISTURE - 5674 BTU/LB
*BASED ON BURNING FUEL PRODUCED IN ONE SHIFT OVER A 24 HOUR DAY
FURNACE-2
ESTIMATED ADDITIONAL ASH 0.04 TPH
FURNACE-1
ESTIMATED ADDITIONAL ASH 0.80 TPH
ELECTROSTATIC PRECIPITATOR
ADDITIONAL FLY ASH 0.2 TPH
INDUCED DRAFT FAN
STACK GASES
SUPPLEMENTARY FUEL - PROCESSING PLANT
POWER PLANT RECEIVING STORAGE AND FEED
EXISTING POWER PLANT
SOLID WASTE TO SUPPLEMENTARY FUEL

Figure 5. Flow diagram of the supplementary fuel processing plant of The City of Chicago - Commonwealth Edison

The light fraction consists of most of the light combustible particles, such as paper, plastics, shredded pieces of wood, leaves, etc., and some noncombustible fines; it contains approximately 85% of the organics in the raw refuse. This fraction leaves the air classifier in the exhaust air stream and is passed through a cyclone separator, which drops the solid material directly into the mouth of the secondary or fine shredder. Here the material is further reduced in size to an average dimension of 3.8 cm (1-1/2 in.). The secondary shredder discharge is conveyed to a hopper over the air lock feeder to the pneumatic transfer system. This system conveys the prepared fuel to the storage bins or silos, located adjacent to the boiler house at the power plant. The storage bins provide extra capacity, thus ensuring a proper supplementary fuel flow to the boilers.

Stored supplementary fuel is retrieved by a mechanical system and blown, as required, into the boilers by pneumatic conveyors that are similar to those for the powdered coal feed. The feed rate is controlled by regulating the speed of the mechanical retrieval system. The supplementary fuel consumption is in fixed proportion, on a heating value basis, to the quantity of coal being consumed.

Dust control is an important feature of the Chicago RDF production concept. Control and collection systems are integrated into the process and the recovered material is added to the prepared fuel at the processing plant just prior to entering the pneumatic transfer system to the storage bins. At the power plant transfer system, air is bled from the bin through a filter baghouse and the collected dust returned to the bin.

The Chicago process was designed over three years ago and though much new work has been done in the RDF field since then, nothing has yet been demonstrated on a large scale that would warrant making changes in Chicago's RDF processing train. The most promising new RDF concept involves trommelling raw refuse prior to primary shredding. This arrangement results in a significant reduction in the amount of material requiring shredding, with attendant reduction in processing power consumption and reduced shredder maintenance. The concept will be tested functionally and economically on a large scale by the Recovery I Project, due to go on stream late in 1976 at New Orleans (Ref. 7).

Material Balance

Table 2 shows a mass balance for the RDF processing plant for an input of 907 Mg/d (1,000 TPD) of raw refuse. The raw refuse composition was determined by testing 680 to 907 kg (1,500 to 2,000 lb) random samples from 30 standard refuse collection vehicles. The samples were hand-sorted and the components classified, weighed, and subjected to physical and chemical analysis. The test program was conducted during late January and early February of 1973; some variation in component percentages during other seasons of the year can be expected. Design was based on these results rather than national average values.

TABLE 2A. RDF MASS BALANCE FOR 907 Mg/d RAW REFUSE INPUT

HHV[a] MJ/kg	Raw Refuse Component	As Rec'd Wt. %	Wt. Mg/d	Light Fraction Mg/d	Light Fraction %	Heavy Fraction Mg/d	Iron Recovery Mg/d	To Disposal Mg/d
13.02	Corrugated box board	3.67	33.3	31.7	4.9	4.9		1.5
13.91	Newspaper	12.73	115.5	113.4	17.6	2.1		2.1
13.51	Magazines/books	3.74	33.9	31.7	5.0	2.2		2.2
12.08	Misc. paper	24.77	224.7	213.2	33.0	11.5		11.5
33.10	Plastics	4.09	37.1	34.5	5.3	2.6		2.6
15.51	Textiles	3.16	28.7	27.2	4.4	1.4		1.4
16.42	Wood	2.23	20.2	16.3	2.5	3.9		3.9
9.37	Leaves, shrubs, grass	2.06	18.7	15.4	2.4	3.3		3.3
10.28	Food waste	10.94	99.2	90.7	14.1	8.5		8.5
19.65	Rubber & leather	1.22	11.1	9.1	1.4	2.0		2.0
4.84	Fines (-2.54 cm)	11.45	103.9	45.4	7.0	58.5	1.4	57.1
1.65	Metals	9.89	89.7		0.3			
	Steel	(9.07)	82.3	1.5		80.7	76.7	4.0
	Aluminum	(0.50)	4.5	1.8		2.7		2.7
	ONF[c]	(0.32)	2.9	0.1		2.8		2.8
0.19	Glass, Ceramics, Stones	10.05	91.2	13.6	2.1	77.6		77.6
		100.00	907	645.7b	100.0	261.4	78.1	183.3
	Moisture	(25%)	(226.8)	(204.1)b	(31.6)b	(22.7)	(0.9)	(21.8)

a. Raw Refuse HHV = 10.19 MJ/kg.

b. Expected moisture content in the storage silos is 30%. The difference is due to moisture loss in the pneumatic systems and amounts to 14.5 Mg/d. Quantity arriving in silos is 631.2 Mg with HHV of 13.20 MJ/kg.

c. Other non-ferrous

TABLE 2B. RDF MASS BALANCE FOR 1000 TONS/DAY RAW REFUSE INPUT

HHV[a] Btu/lb	Raw Refuse Component	As Rec'd Wt. %	Wt. T/D	Light Fraction T/D	Light Fraction %	Heavy Fraction T/D	Iron Recovery T/D	To Disposal T/D
5,600	Corrugated box board	3.67	36.7	35	4.9	1.7		1.7
5,980	Newspaper	12.73	127.3	125	17.6	2.3		2.3
5,810	Magazines/books	3.74	37.4	35	5.0	2.4		2.4
5,193	Misc. paper	24.77	247.7	235	33.0	12.7		12.7
14,230	Plastics	4.09	40.9	38	5.3	2.9		2.9
6,670	Textiles	3.16	31.6	30	4.4	1.6		1.6
7,060	Wood	2.23	22.3	18	2.5	4.3		4.3
4,030	Leaves, shrubs, grass	2.06	20.6	17	2.4	3.6		3.6
4,420	Food waste	10.94	109.4	100	14.1	9.4		9.4
8,450	Rubber & leather	1.22	12.2	10	1.4	2.2		2.2
2,080	Fines (-1 in.)	11.45	114.5	50	7.0	64.5	1.5	63.0
709	Metals	9.89	98.9		0.3			
	Steel	(9.07)	(90.7)	1.7		89.0	84.6	4.4
	Aluminum	(0.50)	(5.0)	2.0		3.0		3.0
	ONF[c]	(0.32)	(3.2)	0.1		3.1		3.1
82	Glass, Ceramics, Stones	10.05	100.5	15	2.1	85.5		85.5
		100.00	1000	711.8[b]	100.0	288.2	86.1	202.1
	Moisture	(25%)	(250)	(225)[b]	(3.16)[b]	(25)	(1)	(24)

[a] Raw Refuse HHV = 4380 Btu/lb.

[b] Expected moisture content in the storage silos is 30%. The difference is due to moisture loss in the pneumatic systems and amounts to 16 TPD. Tonnage arriving in silos is 695.8 with HHV of 5674 Btu/lb.

[c] Other non-ferrous.

The flow diagram (Figure 5) indicates that for a 72 Mg/h (80 TPH) processing rate, 50.4 Mg/h (55.6 TPH), or 70% of the input material, reaches the power plant boiler. The Chicago refuse composition data, which was accumulated during a relatively dry season, had an as-received moisture content of 25%. Table 2 shows the light fraction moisture content as 31.6%. This results from the fact that the water is concentrated in the organic materials and as inorganics are removed, the percentage of moisture in the remaining material is higher. In turn, some moisture will be driven off by energy input during shredding and carried away by the air of the several dust collection and pneumatic handling systems. Based on the St. Louis experience, where data were collected over extended time periods, it is expected that the material fed to the boilers will have a moisture content of approximately 30%. This indicates a loss of nearly 1.2 Mg/h (1.3 TPH) of moisture as the material passes through the system.

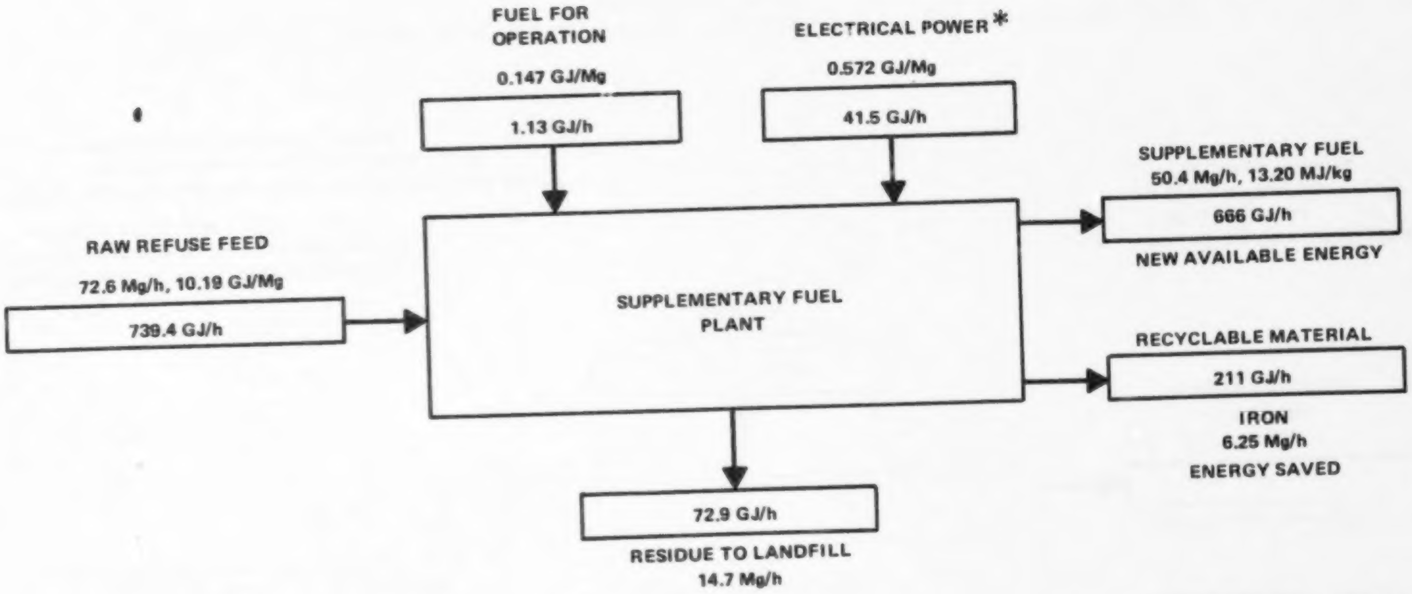
The composition of the raw refuse will vary somewhat from day to day, and noticeably on a seasonal basis. Moisture content of the as-received refuse will also vary according to the seasons. The percentage of yard waste will increase in late spring and summer. These factors will cause some variation in the heating value of the fuel in the storage bins. However, since the quantity of fuel fired will be on a heating value basis, variations will be compensated by adjustment of the quantity of fuel fired.

Another factor affecting the heating value of the fuel is the effectiveness of the air classifier in separating the light and heavy fractions. Since the unit involved is the first of its size in this service, the actual performance will be determined after the unit is placed in operation. If the unit takes off a larger percentage of light fraction, this fraction will contain more inerts and also some larger particles of combustibles. The main effect of this will be to increase the amount of bottom ash in the furnaces and also possibly cause some loss of heat because of incomplete combustion of the larger organic particles in the suspension-fired furnaces.

Energy Balance

Figure 6 presents an energy diagram of the supplementary fuel processing plant, based on a raw refuse input of 72 Mg/h (80 TPH). The refuse energy values used are those anticipated from the material composition shown in Table 2. The HHV of the fuel leaving the processing plant is calculated to be 13.20 MJ/kg (5674 Btu/lb). This is based on calorimetric tests of the refuse mass balance components as found in the test program previously described. Energy content of the RDF stored in the power plant silos amounts to 9.183 GJ/Mg (7.896 x 10^6 Btu/ton) of raw refuse processed.

Table 3 tabulates the energy balance of the system from raw refuse on the processing plant tipping floor through fuel into the boiler combustion zone. This shows a net energy availability of 8.208 GJ/Mg (7.058 x 10^6 Btu/ton) of raw refuse processed or 1985 TJ (1,881 x 10^9 Btu) for a system processing 235.85 Gg (260,000 tons) per year. Also shown is the amount of energy saved by recycling ferrous metals as opposed to processing metal from virgin materials; the saving amounts to 2.904 GJ/Mg (2.497 x 10^6 Btu/ton) of raw refuse

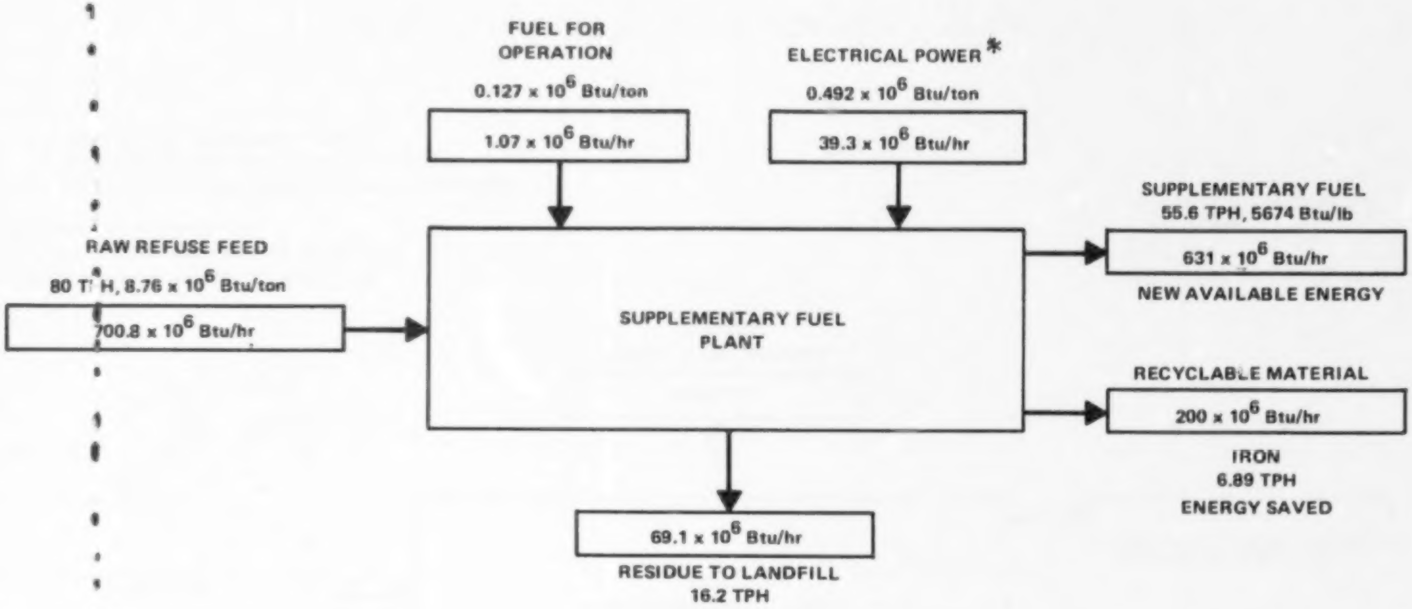

FUEL FOR OPERATION
0.147 GJ/Mg
1.13 GJ/h
ELECTRICAL POWER *
0.572 GJ/Mg
41.5 GJ/h
RAW REFUSE FEED
72.6 Mg/h, 10.19 GJ/Mg
739.4 GJ/h
SUPPLEMENTARY FUEL PLANT
SUPPLEMENTARY FUEL
50.4 Mg/h, 13.20 MJ/kg
666 GJ/h
NEW AVAILABLE ENERGY
RECYCLABLE MATERIAL
211 GJ/h
IRON
6.25 Mg/h
ENERGY SAVED
72.9 GJ/h
RESIDUE TO LANDFILL
14.7 Mg/h

TOTAL ENERGY AVAILABLE
= 877 GJ/h
= 12.1 GJ/Mg
RAW REFUSE PROCESSED

*ELECTRIC POWER GIVEN AS ENERGY IN ELECTRICITY DIVIDED BY POWER PLANT THERMAL EFFICIENCY, 33%

NOTE: ENERGY BALANCE DOES NOT OCCUR BECAUSE OF RECYCLABLE MATERIAL CREDIT AND MISCELLANEOUS SMALL LOSSES.

Figure 6A. Energy diagram of Chicago supplementary fuel processing plant (SI Units).


FUEL FOR OPERATION
0.127 x 10^6 Btu/ton
1.07 x 10^6 Btu/hr
ELECTRICAL POWER *
0.492 x 10^6 Btu/ton
39.3 x 10^6 Btu/hr
RAW REFUSE FEED
80 TPH, 8.76 x 10^6 Btu/ton
700.8 x 10^6 Btu/hr
SUPPLEMENTARY FUEL PLANT
SUPPLEMENTARY FUEL
55.6 TPH, 5674 Btu/lb
631 x 10^6 Btu/hr
NEW AVAILABLE ENERGY
RECYCLABLE MATERIAL
200 x 10^6 Btu/hr
IRON
6.89 TPH
ENERGY SAVED
69.1 x 10^6 Btu/hr
RESIDUE TO LANDFILL
16.2 TPH

*ELECTRIC POWER GIVEN AS ENERGY IN ELECTRICITY DIVIDED BY POWER PLANT THERMAL EFFICIENCY, 33%

NOTE: ENERGY BALANCE DOES NOT OCCUR BECAUSE OF RECYCLABLE MATERIAL CREDIT AND MISCELLANEOUS SMALL LOSSES.

TOTAL ENERGY AVAILABLE
= 831 x 10^6 Btu/hr
= 10.4 x 10^6 Btu/ton
Raw Refuse Processed

Figure 6B. Energy diagram of Chicago supplementary fuel processing plant (English Units).

TABLE 3A. ENERGY RECOVERED/SAVED FROM 72.6 Mg/h SUPPLEMENTARY FUEL SYSTEM (235 872 Mg/y RAW REFUSE PROCESSED)

Energy Used and Saved	MJ/Mg of Raw Refuse	TJ/y
Energy in Raw Refuse	10 188	2 403
Energy in Residue to Landfill	1 005	237
Energy in Supplementary Fuel	9 183	2 166
Fuel Energy Used:		
Fuel required to operate vehicles and front-end	17	4.2
Power required to operate facilities (including Power Plant)	777	184
Building Heating Fuel	180	42.2
Total Energy Required	974	230
Net Fuel Energy Produced	8 209	1 936
Energy Saved:		
0.0781 Mg of steel at 33.7 GJ/Mg	2 904	685
Total Net Energy	11 112	2 621
Net Energy Available as Percent of Raw Energy in Refuse	109%	109%
Equivalent Mg of 23.26 MJ/kg coal	0.43	112 672

TABLE 3B. ENERGY RECOVERED/SAVED FROM 80 TPH SUPPLEMENTARY FUEL SYSTEM (260,000 TPY RAW REFUSE PROCESSED)

Energy Used and Saved	10^3 Btu per Ton of Raw Refuse	10^9 Btu/yr
Energy in Raw Refuse	8,760	2,278
Energy is Residue to Landfill	864	225
Energy in Supplementary Fuel	7,896	2,053
Fuel Energy Used:		
Fuel required to operate vehicles and front-end	15	4
Power required to operate facilities (including Power Plant)	668	174
Building Heating Fuel	155	40
Total Energy Required	838	218
Net fuel Energy Produced	7,058	1,835
0.0861 tons of steel at 29 x 10^6 Btu/ton	2,497	649
Total Net Energy	9,555	2,484
Net Energy Available as Percent of Raw Energy in Refuse (9.555/8,760)	109%	109%
Equivalent tons of 10,000 Btu/lb coal	48	124,200

processed. Thus the total energy saved plus that made available is 11.112 GJ/Mg (9.555 x 10^6 Btu/ton) of raw refuse, or 2 616 TJ (2.48 x 10^{12} Btu) per year. This is equivalent to a saving of 112.66 Gg (124,200 tons) of coal. The two power generating units to which the fuel is supplied have a total capacity of approximately 900 MW. At a 0.8 utilization factor, these units would normally consume approximately 3,150,000 tons of coal per year.

FACILITY DESCRIPTION

Figure 7 shows an external view of the supplementary fuel plant. Figure 8 shows the site plan of the total facility while Figure 9 indicates the processing equipment layout. Elevation sections are shown in Figure 10 and Figure 11 details of the storage bins and material handling equipment on the power plant site. The overall facility is composed of (1) the fuel processing plant and (2) the fuel storage and boiler feed system facility. The project feasibility study and fuel processing plant design were accomplished by Parsons-Consoer, a joint venture of The Ralph M. Parsons Company of Pasadena, California, and Consoer-Townsend and Associates of Chicago, under contract to the Department of Public Works of the City of Chicago. The power plant onsite facility was designed by John Dolio and Associates of Chicago, under contract to the Commonwealth Edison Company.

Fuel Processing Plant

Capacity Analysis--

The plant is equipped with two independent lines each with a design capacity of 72 Mg/h (80 TPH). This provides a great deal of flexibility in plant operation. The city's initial operating plan is to operate one 8-hour shift 5 days per week and process 907 Mg (1,000 tons) of raw refuse per day. Assuming one process line will produce for 7-1/2 hours out of an 8-hour shift, for a rate of 544 Mg (600 tons) per shift, the second line will have to operate only 5 hours per day. The majority of maintenance will be conducted on the second shift. Table 4 shows related material quantities for this mode of operation.

TABLE 4. SUMMARY OF PLANT PRODUCTION, 907 Mg (1000 tons) SHIFT

Product Item	Quantity	
	SI Units	English Units
Raw refuse processed per day (normal operation)	907 Mg	1,000 tons
Raw refuse processed per week	4535 Mg	5,000 tons
Raw refuse processed per year	235 Gg	260,000 tons
Supplementary fuel delivered per day (normal operation)	631 Mg	696 tons
Supplementary fuel delivered per week	3157 Mg	3,480 tons
Supplementary fuel delivered per year	164 Gg	181,000 tons
Fuel heating value	13.19 GJ/Mg	11.35 x 10^6 Btu/ton
Fuel heating value per year	2167 TJ	2,054,000 x 10^6 Btu
Ferrous product recovered per day (normal operation)	78 Mg	86 tons
Ferrous product recovered per year	20.2 Gg	22,300 tons
Residue to landfill per day (normal operation)	183 Mg	202 tons
Residue to landfill per year	47.6 Gg	52,500 tons

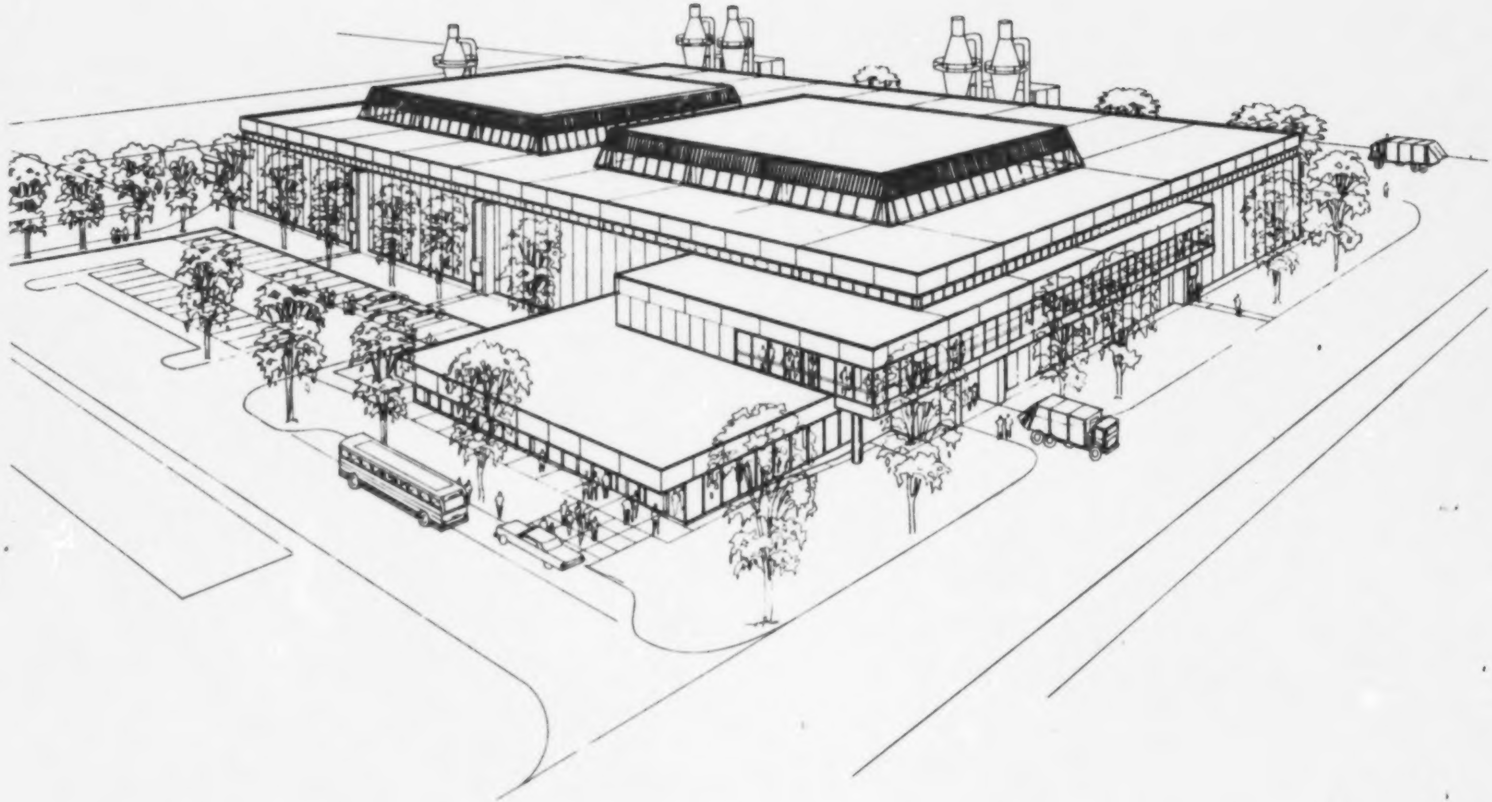


Figure 7. City of Chicago supplementary fuel plant

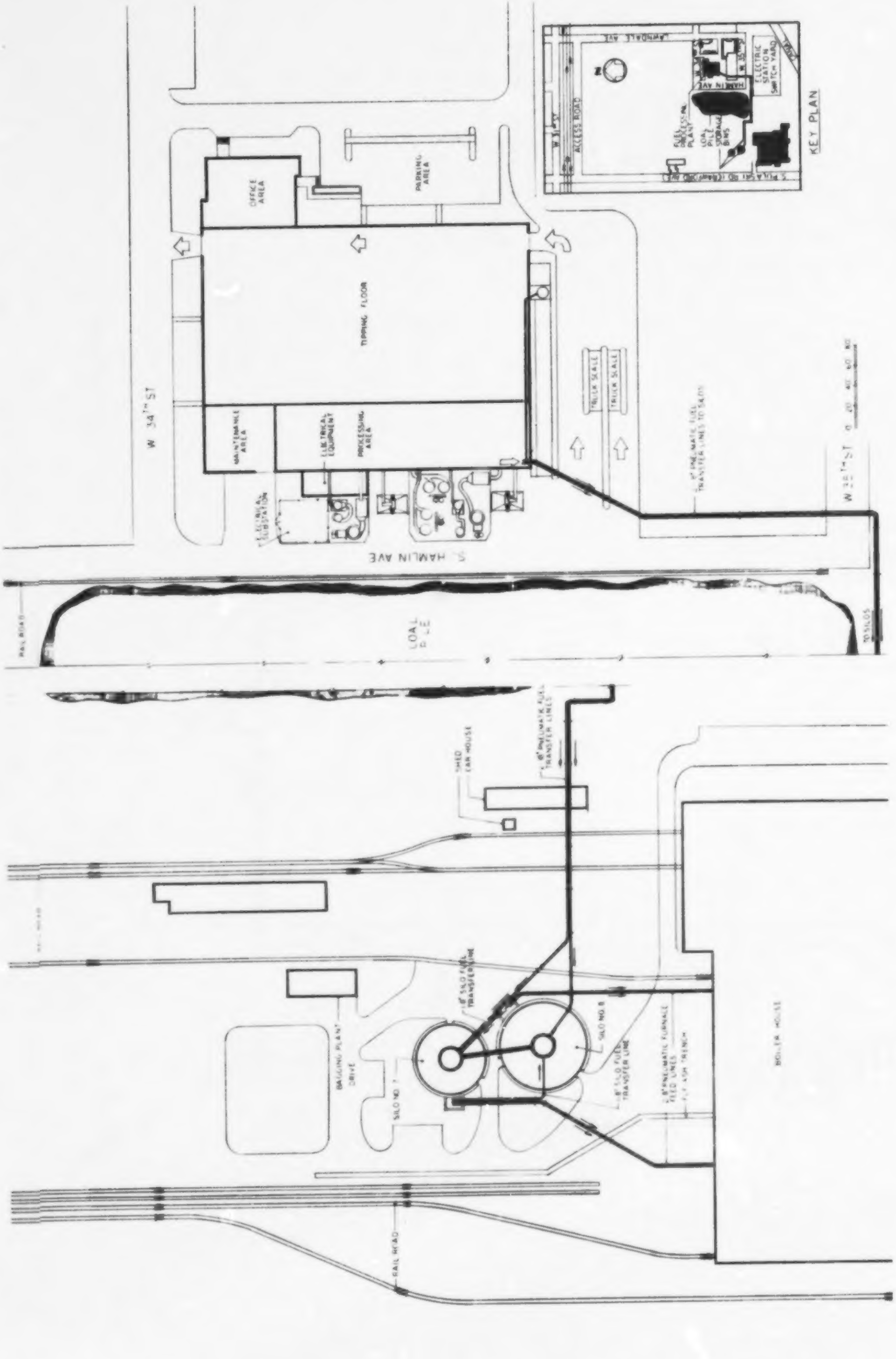

W 34TH ST
OFFICE AREA
PARKING AREA
TIPPING FLOOR
MAINTENANCE AREA
ELECTRICAL EQUIPMENT
PROCESSING AREA
ELECTRICAL SUBSTATION
TRUCK SCALE
TRUCK SCALE
W 35TH ST
S. HAMLIN AVE
RAIL ROAD
COAL PILE
TO SILOS
SHED
CAR HOUSE
SILO NO 7
SILO NO 8
BAGGING PLANT DRIVE
BOILER HOUSE
RAIL ROAD
KEY PLAN
ACCESS ROAD
ELECTRIC STATION SWITCH YARD
HAMLIN AVE
LAWNDALE AVE
S. PULASKI RD

Figure 8. Site plan of the City of Chicago - Commonwealth Edison facility.

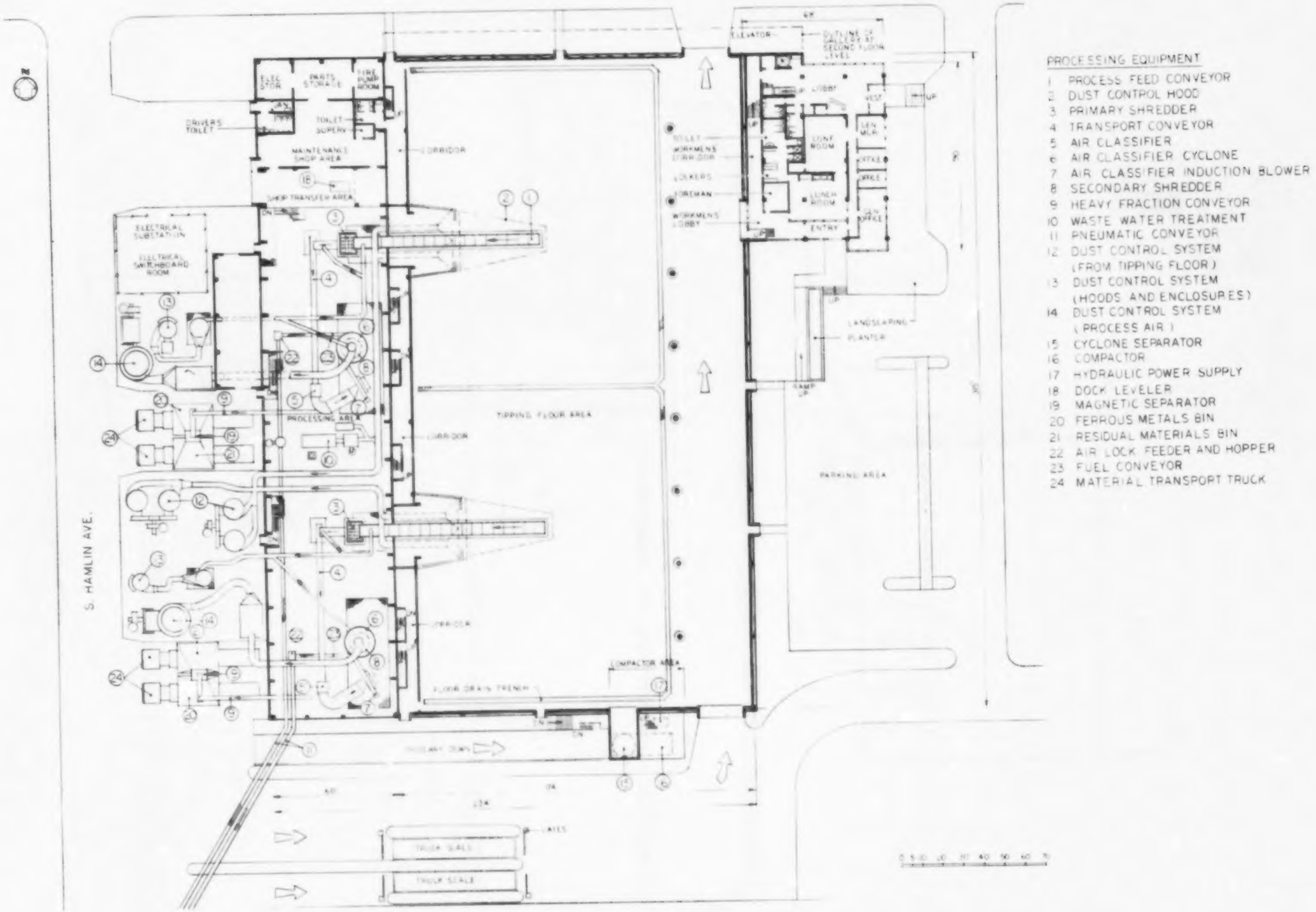
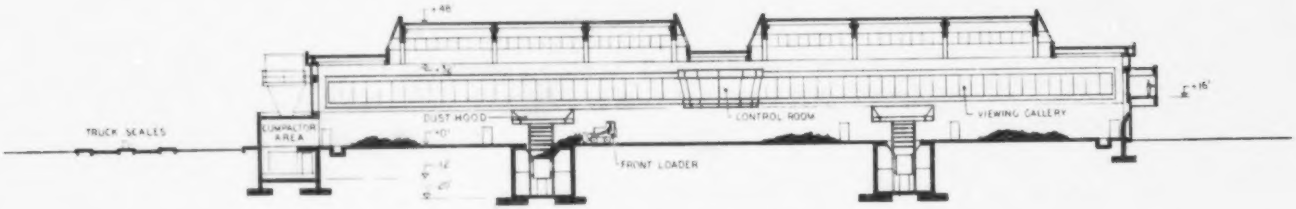
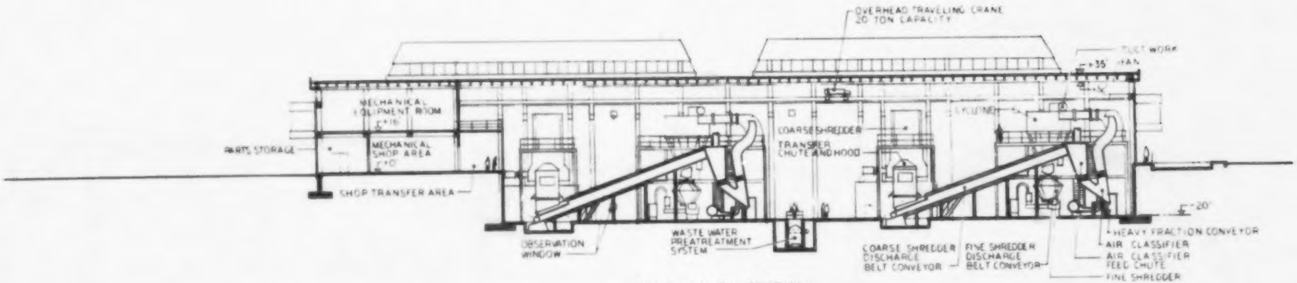

PROCESSING EQUIPMENT
1 PROCESS FEED CONVEYOR
2 DUST CONTROL HOOD
3 PRIMARY SHREDDER
4 TRANSPORT CONVEYOR
5 AIR CLASSIFIER
6 AIR CLASSIFIER CYCLONE
7 AIR CLASSIFIER INDUCTION BLOWER
8 SECONDARY SHREDDER
9 HEAVY FRACTION CONVEYOR
10 WASTE WATER TREATMENT
11 PNEUMATIC CONVEYOR
12 DUST CONTROL SYSTEM (FROM TIPPING FLOOR)
13 DUST CONTROL SYSTEM (HOODS AND ENCLOSURES)
14 DUST CONTROL SYSTEM (PROCESS AIR)
15 CYCLONE SEPARATOR
16 COMPACTOR
17 HYDRAULIC POWER SUPPLY
18 DOCK LEVELER
19 MAGNETIC SEPARATOR
20 FERROUS METALS BIN
21 RESIDUAL MATERIALS BIN
22 AIR LOCK FEEDER AND HOPPER
23 FUEL CONVEYOR
24 MATERIAL TRANSPORT TRUCK
S. HAMLIN AVE.
TIPPING FLOOR AREA
PROCESSING AREA
CORRIDOR
ELECTRICAL SUBSTATION
ELECTRICAL SWITCHBOARD ROOM
PARTS STORAGE
FIRE PUMP ROOM
DRIVERS TOILET
TOILET SUPERV.
MAINTENANCE SHOP AREA
SHOP TRANSFER AREA
ELEVATOR
OUTLINE OF GALLERY AT SECOND FLOOR LEVEL
LOBBY
CONF. ROOM
LUNCH ROOM
ENTRY
OFFICE
TOILET
WORKMENS CORRIDOR
LOCKERS
FOREMAN
WORKMENS LOBBY
LANDSCAPING PLANTER
RAMP UP
UP
PARKING AREA
COMPACTOR AREA
FLOOR DRAIN TRENCH
TRUCK SCALE
TRUCK SCALE
0 5 10 20 30 40 50 60 70

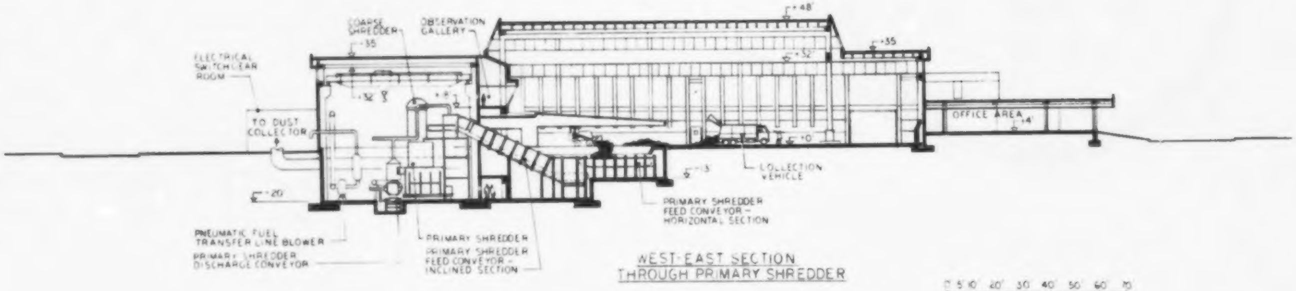
Figure 9. Floor plan of City of Chicago supplementary fuel plant.


+48
+16'
TRUCK SCALES
COMPACTOR AREA
DUST HOOD
+0'
-12
-20
FRONT LOADER
CONTROL ROOM
VIEWING GALLERY

SOUTH-NORTH SECTION
THROUGH TIPPING FLOOR

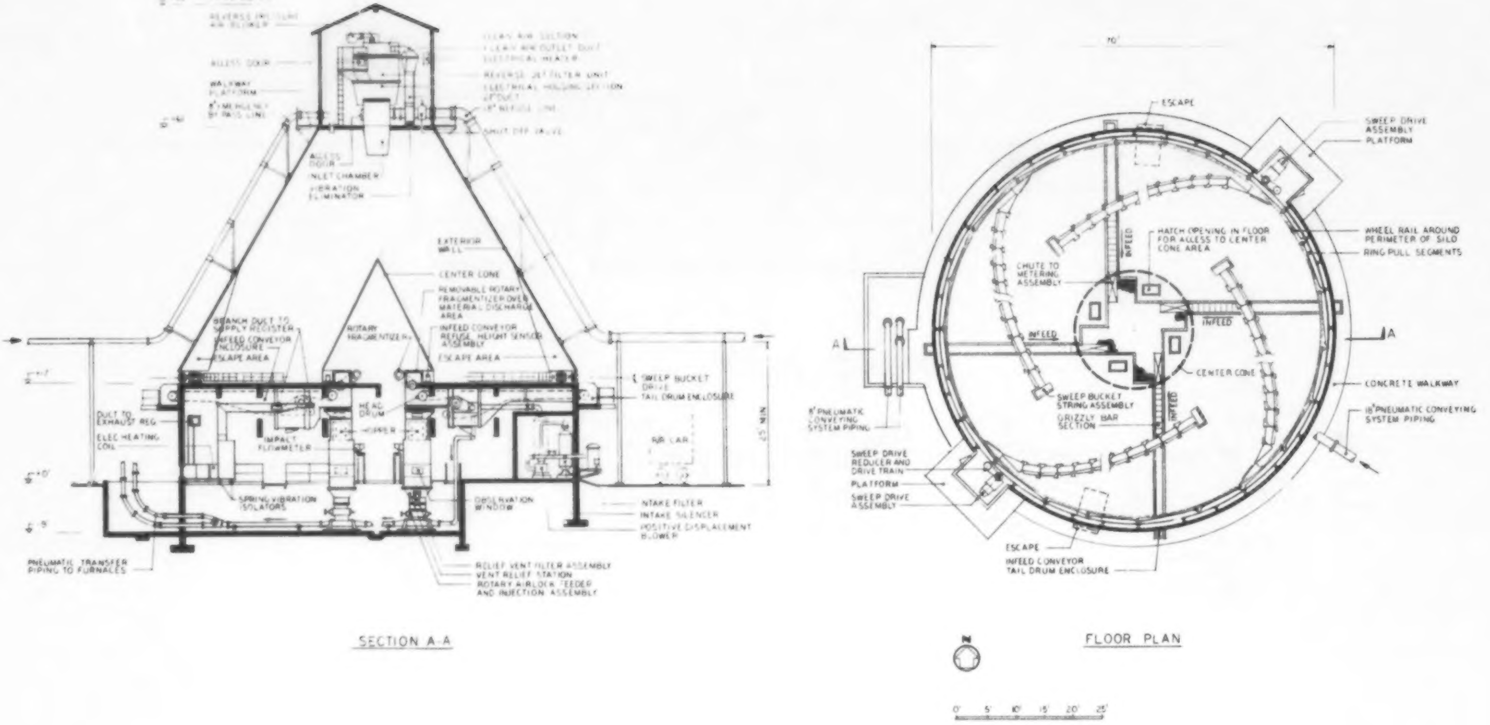

OVERHEAD TRAVELING CRANE
20 TON CAPACITY
DUCT WORK
FAN
+35'
CYCLONE
MECHANICAL EQUIPMENT ROOM
+16'
PARTS STORAGE
MECHANICAL SHOP AREA
+0'
SHOP TRANSFER AREA
COARSE SHREDDER
TRANSFER CHUTE AND HOOD
-20'
OBSERVATION WINDOW
WASTE WATER PREATREATMENT SYSTEM
COARSE SHREDDER DISCHARGE BELT CONVEYOR
FINE SHREDDER DISCHARGE BELT CONVEYOR
HEAVY FRACTION CONVEYOR
AIR CLASSIFIER
AIR CLASSIFIER FEED CHUTE
FINE SHREDDER

NORTH-SOUTH SECTION
THROUGH PROCESSING AREA


+48'
+35
+32'
COARSE SHREDDER
OBSERVATION GALLERY
-35
ELECTRICAL SWITCHGEAR ROOM
+32'
+8'
TO DUST COLLECTOR
-20'
OFFICE AREA
+4'
+0
-13'
COLLECTION VEHICLE
PRIMARY SHREDDER FEED CONVEYOR - HORIZONTAL SECTION
PNEUMATIC FUEL TRANSFER LINE BLOWER
PRIMARY SHREDDER DISCHARGE CONVEYOR
PRIMARY SHREDDER
PRIMARY SHREDDER FEED CONVEYOR - INCLINED SECTION
0 5 10 20' 30 40' 50 60' 70

WEST-EAST SECTION
THROUGH PRIMARY SHREDDER

Figure 10. Elevation sections of The City of Chicago supplementary fuel plant.



SECTION A-A

FLOOR PLAN

DRIVE MOTOR
REVERSE PRESSURE AIR BLOWER
ACCESS DOOR
WALKWAY PLATFORM
8" EMERGENCY BY PASS LINE
CLEAN AIR SECTION
CLEAN AIR OUTLET DUCT
ELECTRICAL HEATER
REVERSE JET FILTER UNIT
ELECTRICAL HOUSING SECTION
18" REFUSE LINE
SHUT OFF VALVE
ACCESS DOOR
INLET CHAMBER
VIBRATION ELIMINATOR
EXTERIOR WALL
CENTER CONE
REMOVABLE ROTARY FRAGMENTIZER OVER MATERIAL DISCHARGE AREA
BRANCH DUCT TO SUPPLY REGISTER
INFEED CONVEYOR ENCLOSURE
ESCAPE AREA
ROTARY FRAGMENTIZERS
INFEED CONVEYOR REFUSE HEIGHT SENSOR ASSEMBLY
ESCAPE AREA
SWEEP BUCKET DRIVE
TAIL DRUM ENCLOSURE
DUCT TO EXHAUST REG
ELEC HEATING COIL
HEAD DRUM
HOPPER
IMPACT FLOWMETER
R/R CAR
25' MIN
SPRING VIBRATION ISOLATORS
OBSERVATION WINDOW
INTAKE FILTER
INTAKE SILENCER
POSITIVE DISPLACEMENT BLOWER
PNEUMATIC TRANSFER PIPING TO FURNACES
RELIEF VENT FILTER ASSEMBLY
VENT RELIEF STATION
ROTARY AIRLOCK FEEDER AND INJECTION ASSEMBLY
70'
ESCAPE
SWEEP DRIVE ASSEMBLY
PLATFORM
HATCH OPENING IN FLOOR FOR ACCESS TO CENTER CONE AREA
WHEEL RAIL AROUND PERIMETER OF SILO
RING PULL SEGMENTS
CHUTE TO METERING ASSEMBLY
INFEED
INFEED
INFEED
INFEED
A
A
CENTER CONE
CONCRETE WALKWAY
SWEEP BUCKET STRING ASSEMBLY
GRIZZLY BAR SECTION
8" PNEUMATIC CONVEYING SYSTEM PIPING
18" PNEUMATIC CONVEYING SYSTEM PIPING
SWEEP DRIVE REDUCER AND DRIVE TRAIN
PLATFORM
SWEEP DRIVE ASSEMBLY
ESCAPE
INFEED CONVEYOR TAIL DRUM ENCLOSURE
N
0' 5' 10' 15' 20' 25'

Figure 11. Storage bins with material handling equipment on the power plant site.

As loads increase, it would be possible to run both lines 2 shifts per day and increase production to 15-1/2 hours or 2250 Mg (2,480 tons) of raw refuse processed and 1566 Mg (1,726 tons) of fuel produced. Presuming, on a very conservative basis, that maintenance is required 1 line-shift for each 2 line-shifts of operation, it is possible to stagger operations so that only one line is down for maintenance on any shift. Optimistically, operating experience may show maintenance averaging out to one line-shift of maintenance for five line-shifts of operation. In this case, the two lines could process 2866 Mg (3,160 tons) of raw refuse and produce 1996 Mg (2,200 tons) of fuel in 24 hours of operation. Operating experience will establish the reality of the situation.

Plant Location and Layout--

Based on the 1972 feasibility study, a 22 250 m^2 (5-1/2 acre) site adjacent to Commonwealth Edison's Crawford Station was chosen for the processing plant. The processing plant building is a reinforced concrete structure. The floor, totally under roof, has a working area of 3307 m^2 (35,600 ft^2) and is able to store as much as 1592 Mg (1,750 tons) of raw refuse when piled 3.05 m (10 ft) high, or nearly 2 shifts' production. A control room provides supervision of tipping floor operations and monitors the processing area by closed circuit television. The whole processing area is serviced by an overhead bridge crane. The office area is a two-story office and shop-type building attached to the front of the main structure. This building contains a visitors' entrance to a viewing gallery.

The outside area contains the storage bins and truck loading facilities for the recovered metals and residue, a compactor for loading fuel or raw refuse, the exhaust fans and filter baghouses for plant ventilation and dust control systems, and the electrical substation yard.

Plant Operation--

Trucks entering the processing facility are controlled by traffic signals, and the entire plant is remotely controlled by appropriate electronic equipment. The flow of material is continuous from recording of the incoming refuse to finished product with control of the processing being accomplished through a combination of the rate at which waste is loaded onto the process feed conveyor from the tipping floor and variation of conveyor speed.

Ferrous metals are recovered from each line at an approximate rate of 18 Mg (20 tons) every 3 hours. Disposal of this material will be determined at the time a ferrous material sales contract is negotiated. The residue is disposed of as landfill. An 18 Mg (20 ton) load of residue for landfill comes from each processing line every 1-1/4 hour.

Process Equipment Trains--

Redundancy is provided in the form of two trains of processing equipment. Dust control is accomplished by hooding or shrouding equipment or areas where dust is generated and by maintaining negative air pressure in those areas. The collected air is passed through baghouse filters to remove the dust before being exhausted to the atmosphere.

The most important pieces of equipment installed are described in the following paragraphs.

The front-end loaders are heavy duty 5 cubic yard machines utilized for handling the raw refuse on the tipping floor. They are diesel-powered articulated vehicles with foam-filled rubber tires. Four of these machines are required, with three normally handling two operating lines and the fourth is a spare.

The process feed conveyor is a two-section steel Z-bar conveyor, 2.44 m (96 in.) in width. The first horizontal section is 9.14 m (30 ft) long, and is mounted in a pit in the floor with the conveying surface 1.83 m (6 ft) below tipping floor level. It has a reversible hydraulic drive and runs from 0 to 3.05 m (10 ft) per minute. The second section is also reversible and runs at 3 times the speed of the first. The purpose of having two sections operating with a speed differential is to help break up the refuse and more evenly distribute the load over the conveyor surface. This is expected to result in a more uniform feed rate to the shredder. The Z-bar slats are formed from at least 9.5 mm (3/8 in.) thick plate and are suitably reinforced structurally. The pit has steel-plated sides sloping into the conveyor at an angle of 30° from the vertical. The second section sloped approximately 30° from the horizontal that raises the material to the primary shredder mouth. The drive mechanisms are remotely controlled from the central control room, and are electrically interlocked with the drive motor of the primary shredder.

The primary or coarse shredder is a horizontal, reversible hammermill rated for continuous duty at 72 Mg/h (80 TPD); it is direct driven by a 746 kW (1,000 HP) induction motor running at 900 rpm. The machine has a conveyor entrance with a heavy steel hood to confine heavy material ballistically thrown by the rotating hammers. The grate openings are set so that all material intended for further processing will have a maximum dimension not exceeding 20.3 cm (8 in.). The machine is designed with easy access to those parts subject to rapid wear, such as hammers, impact plates, grates, and liners. The design also incorporates easy-opening, hydraulically actuated access doors in the grinding chamber. The impact plates are mounted in such a manner that the hammer clearance may be hydraulically adjusted to compensate for wear.

A suitably matched, heavy duty, steel pan-type conveyor is provided to catch the discharge material from the shredder. (The coarsely shredded refuse may at times contain metal pieces ejected at high velocity.) This conveyor discharges onto the coarse material conveyor. The end emerging from under the shredder is enclosed with a metal dust control shroud that interfaces with a dust cover on the coarse material conveyor.

The transport conveyor is a troughed rubber belt, 1.83 m (72 in.) wide, sloped 20° to horizontal, and is electrically driven at a speed of approximately 1.27 m/s (250 ft/min). It carries the coarse shredded material to the material intake of the air classifier and has a sectionalized dust hood that can be opened by section for operational inspection.

The air classifier accomplishes air/density separation of the shredded material at a continuous rated capacity of 72 Mg/h (80 TPH). The system includes the air classifier proper, a special light material conveying duct, 186 kW *(250 HP) material handling blower, and a cyclone-type material separator.

The coarsely shredded material falls continuously across a steeply slanted vibrating tray. Below the mid-point, a strong stream of air enters through slots and passes upward through the vibrationally energized bed of material. The light fraction is captured by the air stream and is carried out of the separator and through a cyclone separator, while the heavy fraction continues to the end of the tray and falls out onto a conveyor. Induced draft air enters the separator at both the material inlet and the heavy fraction outlet, while the air entering the tray slots is blown in by forced draft blowers. Provision is made to "tune" the system for best separation by adjusting the various air stream velocities. The light fraction drops from the bottom of the cyclone separator into the secondary shredder. The heavy density material from the bottom of the air classifier is conveyed to a magnetic separator and then dropped into transport trucks.

The secondary shredder completes the grinding of the combustible material to an average dimension of 3.8 cm (1-1/2 in.). It has a continuously rated capacity of 54 Mg/h (60 TPD), three quarters that of the primary shredder. It is a heavy duty vertical ring-type grinder, gear driven by two 560 kW (750 HP) electric motors.

The fuel conveyor receives the discharge of the secondary shredder. It is a rubberized, troughed and cleated belt 1.37 m (54 in.) wide, and runs at a speed of 1 m/s (200 ft/min). This conveyor leads to the air lock feed hopper and is equipped with catwalks and a sectionalized metal dust cover that can be easily opened for inspection and maintenance.

The air lock feeder has close-clearance rotary paddles, which introduce the processed fuel into the pneumatic conveyor system pipeline. An enclosed hopper receives the material from the secondary discharge conveyor to feed the air lock. A cyclone separator is mounted on this hopper to separate out solid material conveyed in the pneumatic dust conveyor transporting the material collected from various dust collection systems.

The pneumatic conveyor system carries the processed fuel through two parallel 45.7 cm (18 in.) pipes about 488 m (1,600 ft), from the processing plant to the two storage silos at the power plant. Each line receives air from 448 kW (600 HP) positive displacement rotary blowers, normally discharging at a differential pressure of 20.7 to 34.5 kPa (3-5 psig). The lines are cross-connected at the processing plant end so that either blower can operate either pipeline and either pipeline can feed either storage bin. A branch line can conduct material to a cyclone separator that feeds a transfer truck loading compactor.

The heavy density material conveyor is a flat, rubber-cleated belt, with stationary metal sides to retain the conveyed material. It is a constant speed, electric-drive machine, and is sized to handle the material quantities indicated on the flow diagram (Figure 5), plus 25%. The conveyor discharges onto a vibrating conveyor which evenly spreads the material and discharges it close to the face of the magnetic separator.

The magnetic separator is a standard drum-type permanent magnet that picks up the ferrous material in the heavy fraction and deflects it into the ferrous storage bin. The unit is mounted on top of the ferrous and residual materials retention bin assembly.

The material retention bins are bottom-dumping bins for holding the ferrous and residual materials. They are designed as enlarged chutes that receive the product material streams leaving the magnetic separator, and have sufficient capacity to retain the material, when the doors are closed, a long enough period of time (about 1/2 hour) to exchange a full truck for an empty one.

The material transport trucks for carrying residue to landfill are open top dumpers with an 18 Mg (20 ton) minimum capacity each. They are powered by heavy-duty, diesel tractors.

The dust control systems include three air moving and dust control units connected to each processing line. One system consists of a hood suspended over the coarse shredder feed conveyor pit, necessary ducting, a large filter baghouse, and an exhaust fan. The approximate air-handling requirement is 37.52 m^3/s (79,500 CFM). This system maintains proper air quality for workers in the tipping floor area and also controls dust there. The largest concentrated dust generating area is the feed conveyor pit. By exhausting air at this point, currents are induced that sweep the tipping floor and move dust generated from truck unloading toward the pit for ultimate removal. The filter baghouse collects the dust and prevents atmospheric contamination outside the building. This system only handles fine airborne dust.

A second major system is for air classifier dust control. This unit handles approximately 31.86 m^3/s (67,500 CFM) of air plus moisture (picked up from the waste) and processes the dust-laden material passed through the air classifier. Large particles of paper or sheet plastic are kept out of the baghouse by using a dropout box and a secondary cyclone ahead of the filter baghouse.

A third and smaller system has a capacity of approximately 7.08 m^3/s (15,000 CFM) and handles dust laden air from the various dust hoods and other collection points in the process train.

The baghouses used are continuously self-cleaning, with antistatic bags as filters. The baghouses, dropout boxes, and secondary cyclones are equipped with rotary air locks that pass the collected material into a pneumatic conveyor system for transport to the air lock feed hopper, where it is added to the processed fuel.

Auxiliary Equipment--In addition to the process equipment, several major support items are essential to operation of the plant.

The waste water treatment system provides the tipping area and process floors with a drainage system that may pick up substantial amounts of solid materials during periods of heavy water flow, such as washdown operations or fire-fighting. The drainage water passes through a wastewater pre-treatment system consisting of scum and solids collecting equipment. The clear water flows to the sewer system.

A travelling bridge crane serves the process area. It moves overhead with a variable speed drive and inching control, and is equipped with an 18 Mg (20 ton) hook.

A house air supply of sufficient capacity to handle such items as filter baghouse operation, instrumentation, air-operated controls, pneumatic tools, and other maintenance operations is provided. The supply provides 100% redundance in the form of two standard 93 kW (125 HP), 689 kPa (100 psi), packaged units.

Two truck scales are used to weigh refuse delivery trucks in the entrance roadway. These are standard weighing scales of 45 Mg (50 ton) capacity, 21.3 m (70 ft) long and 3.05 m (10 ft) wide. They are automatic, including entrance and exit gates, and are provided with remote data reading, recording equipment, and manual controls located in the plant control room.

The heating, ventilating, and air conditioning system for the facility consists of a number of independently controlled areas. The tipping floor area is unheated because of the large quantity of ventilation air required to remove equipment exhaust gases. The truck entrance and exit doors remain open during plant operations (except in severe weather) to allow air to sweep across the tipping floor to the hoods over the conveyor pits. During periods when the process equipment is not running and the main exhaust system is off, ventilation is provided by roof-mounted fan units. Electric heating elements are embedded in the floor for a distance of 3.7 m (12 ft) around the conveyor pits. This prevents the formation of floor ice in cold weather close to the pits, which might be a hazard to the front-end loader operations.

The processing area has large quantities of air passing through it because of requirements for the air classifiers. Incoming air is warmed to a minimum of 13°C (55°F) in accordance with the City building code by large heating units mounted against the inside of the rear process room wall. Wall-mounted gas-fired space heaters are provided near the working floor levels during periods when the process equipment is down for maintenance.

The office and shop areas include offices, lunchroom, toilets, and locker rooms. These are heated and air-conditioned. A central chilled water system is provided for refrigeration. Other areas are provided with gas-fired heated and filtered air from a central air handling system. The control room is heated, ventilated, and air-conditioned, and the visitors' gallery is air conditioned and, in winter, heated by baseboard type electrical heaters.

A fuel supply is required only for the vehicles, and this is provided by the existing facility at the street maintenance shop already on the property.

A fire protection system offering complete sprinkler coverage is provided to protect the plant, in accordance with local and national codes. All areas have a wet system except the tipping floor area, which has a dry type because the room is subjected to freezing temperatures. The tipping floor is also provided with fire hoses to combat refuse fires anywhere on the floor. Other areas are provided with wall-mounted hand extinguishers and hoses in accordance with established standards.

The electric power distribution system within the facility is supplied by the Commonwealth Edison Company through a transformer station located on the property. Two 7,500 kVA transformers receive high voltage power and deliver 4,160 V, 3 phase, 60 Hz power to the facility metering panels. The facility distribution system consists of two duplicate systems of 7,500 kVA each. Tie-line switching is provided so that either Edison transformer can feed either load center substation and distribution system. Each system carries one of the processing lines plus some auxiliary equipment. Motors of 298 kW (400 HP) or larger are supplied by 4,160-V distribution sections of each system.

The remote control system is located in the control room. Central panels are provided for each line for independent operation. The material processing rate is controlled by the rate at which the front loaders place material on the primary feed conveyor and also by the central process controller adjusting the speed of the primary feed conveyor. Each line is set up with interlocked controls for automatic sequential start-up and shutdown of each major component of the line. The central control system can manually override the automatic programming. Local start-stop controls are provided at each piece of equipment to permit emergency shutdown or to facilitate maintenance operation.

Power Plant Facilities

Capacity Analysis--

The boilers of Generating Units 7 and 8 of the Crawford Station have been modified to receive supplementary fuel. Both units are similar in configuration, with their operating cycles employing separately-fired reheat sections. The main furnace and the reheat furnace of both units are fitted to fire supplementary fuel. Table 5 shows pertinent generating unit data.

Unit 7 is rated at 238,360 kW with a steaming rate of 658 000 kg/h (1,450,000 lb/hr) at 16.201 MPa (2,350 psia) and 565°C (1,050°F). The reheat section operates at approximately 3.826 MPa (555 psia) and reheats to the original temperature. The unit is equipped to feed up to 13.6 Mg/h (15 TPH) of supplementary fuel into the main furnace for a burning rate of approximately 7.27% of the heat requirement. The maximum feed capability to the reheat furnace is also 13.6 Mg/h (15 TPH), but at 10% of the heat release, the feed rate would be 54.0 Mg/d (59.5 TPD). The total unit would therefore consume 381 Mg/d (420 TPD), requiring up to 548 Mg/d (604 TPD) of raw refuse to be processed.

Unit 8 is rated at 358 160 kW with a steaming rate of 998 000 kg/h (2,200,000 lb/hr). The steam conditions are the same as for Unit 7 except that reheat pressure is 4.102 MPa (595 psia). The unit is equipped to feed up to 21.8 Mg/h (24 TPH) of supplementary fuel into the main furnace or a

TABLE 5A. CRAWFORD STATION GENERATING UNIT DATA (in SI units)

Item	Unit No. 7	Unit No. 8
1. Name Plate Rating - kW	239 360	358 160
2. Steaming Rate - kg/h	658 000	998 000
3. Steam Pressure - MPa	16.201	16.201
4. Steam Temperature - °C	565	565
5. Reheat Pressure - MPa	3.826	4.102
6. Reheat Temperature - °C	565	565
7. RDF - Max. Firing Rate - Main Furnace - Mg/h/Mg/d	13.6/327	21.8/522
8. RDF - Max. Firing Rate - Reheat - Mg/h/Mg/d	13.6/327	21.8/522
9. RDF - Max. Main Furnace Burning Rate - % Heating Requirement	7.27	7.66
10. RDF - Reheat Furnace Firing Rate @ 10% Heating Requirement - Mg/h/Mg/d	2.25/54.0	3.12/74.9
11. RDF - Total Required at 10% Max. Burning Rate or Max. Capability - Mg/h/Mg/d	15.9/381	24.9/597
12. Raw Refuse - Max. Daily Process Requirement - Mg	548	858

TABLE 5B. CRAWFORD STATION GENERATING UNIT DATA (in English units)

Item	Unit No. 7	Unit No. 8
1. Name Plate Rating - kW	239,360	358,160
2. Steaming Rate - lb/hr	1,450,000	2,200,000
3. Steam Pressure - psia	2,350	2,350
4. Steam Temperature - °F	1,050	1,050
5. Reheat Pressure - psia	555	595
6. Reheat Temperature - °F	1,050	1,050
7. RDF - Max. Firing Rate - Main Furnace - TPH/TPD	15/360	24/576
8. RDF - Max. Firing Rate - Reheat - TPH/TPD	15/360	24/576
9. RDF - Max. Main Furnace Burning Rate - % Heating Requirement	7.27	7.66
10. RDF - Reheat Furnace Firing Rate at 10% Heating Requirement - TPH/TPD	2.48/59.5	3.44/82.6
11. RDF - Total Required at 10% Max. Burning Rate or Max. Capability - TPH/TPD	17.5/420	27.4/658
12. Raw Refuse - Max. Daily Process Requirement - Tons	604	946

burning rate of 7.67% of the heating requirement. The feed capability to the reheat furnace is also 21.8 Mg/h (24 TPH), which is several times the anticipated 10% burning rate, but at 10% the feed rate would be 3.12 Mg/h (3.44 TPH). The total unit burning rate is 24.8 Mg/h (27.4 TPH) or 597 Mg/d (658 TPD), requiring up to 858 Mg/d (946 TPD) of raw refuse to be processed.

The total RDF consumption of both units running at name-plate rating would be 978 Mg/d (1,078 TPD), requiring 1 406 Mg (1,550 tons) of raw refuse to be processed. The average load factor for both units is such that the processing plant load will probably not exceed 907 Mg/d (1,000 TPD). At some later date it might be advantageous to increase the capacity of the main furnace feed systems so that a higher rate of RDF could be burned and thereby better advantage be taken of the processing plant capacity.

Facility Layout and Features--

The route of the RDF pneumatic transfer lines is approximately 488 m (1,600 ft) long from the interior of the processing plant to the silos. Two storage silos are provided, one of 1 700 m^3 (60,000 ft^3) capacity and the other of 2 550 m^3 (90,000 ft^3). The smaller one feeds Unit 7 and the larger one Unit 8. Although the average density of material in the storage silos has yet to be well established, it is anticipated that they will hold 272 Mg (300 tons) and 408 Mg tons) respectively of RDF. This will permit the processing plant to operate on one shift per day and the fuel firing to continue around the clock. Firing on weekends is not contemplated unless there happens to be left-over fuel in the silos.

The silos shown in Figure 11 are designed by Atlas Systems Inc., of Spokane, Washington. Atlas also furnishes the patented material retrieval and handling equipment. The silo is an inverted cone, in the top center of which is the end of the pneumatic transfer pipeline from the processing plant. The material leaves the pipeline and falls in a conical pile on the concrete floor. The air from the pneumatic transfer line is exhausted to atmosphere by an exhaust fan pulling through a dust filter baghouse.

The mechanical equipment is housed in a room under the silo floor, the walls of which provide the outer foundations for the silo. The retrieval mechanism consists of a four-unit (located 90° apart) sweep-bucket chain that is dragged around the floor of the silo by a chain drive mechanism circling the periphery of the floor. The sweep buckets drag the material from the edge of the pile and cause it to fall onto belt conveyors installed in trenches in the silo floor. Four of these are provided which feed radially inward (in this case, but could work outwardly) to discharge the material into hoppers above the rotary airlocks feeding the pneumatic pipelines to the furnaces. A fragmentizer is provided at the discharge of each conveyor to break up any large agglomerates of caked material that may come down the conveyor. The hoppers over the airlocks contain impact-sensitive flowmetering devices that measure the weight of material entering the airlocks. They are equipped with a diverting mechanism for taking weight samples for calibration purposes. These measurements, plus periodic heating value analyses of samples of the material, form the basis for Commonwealth Edison's payments to the City for fuel value received. The sweep bucket system and conveyors have variable speed electric drives that are remotely controlled from the boiler control center to regulate the RDF feed rate to the furnaces.

The silos are connected to the furnaces by four 20.3 cm (8 in.) pneumatic material conveyors. The smaller silo is connected to Unit 7 and the larger silo to Unit 8. Each line is powered by its own 74.6 kW (100 HP) positive displacement rotary blower. In addition, each silo system has a diverter valve and transfer line to the other silo so that, if necessary, fuel may be transferred between silos. The length of the transfer lines to the boilers is approximately 152 m (500 ft), including change in elevation.

Modifications to the boilers, to allow for the introduction of supplementary fuel, are relatively minor. They involve simple penetration of the windbox and furnace wall by the pneumatic fuel transfer lines and mounting of elevating fuel injector nozzles at the end of the lines, inside the furnace wall. Some modification is also required in the boiler control system to provide for regulation of the RDF feed rate and to handle possible changes in the boiler operating characteristics when firing RDF.

The silos are provided with a complete interior sprinkler system for fire protection. An ultrasonic height detector is built into each silo for continuous monitoring of the fuel level. These instruments are also connected to visual display panels in the processing plant control room as well as in the power plant control center.

The additional bottom ash resulting from the supplementary fuel does not place an excessive burden on the existing ash handling system, and the existing electrostatic precipitators on the boiler exhaust gas systems are expected to control the additional fly ash generated.

CONSTRUCTION COSTS

The design and construction costs, as given in Table 6 are considered to be very accurate, being based on fixed price contracts for construction and equipment procurement. The mid-point of construction for this project was the fourth quarter of 1975. The costs cover construction costs only and do not include construction management, working capital, start-up, or other costs normally considered in financing arrangements. The City acted as its own construction manager for the processing plant and Commonwealth Edison provided management for the power plant facility construction.

OPERATING COSTS

Operating costs include direct labor, maintenance services and supplies, utilities, fuel, and residual material disposal costs. The estimates are reported here on an annual basis and are summarized separately for the processing plant and the power plant facility.

TABLE 6. DESIGN AND CONSTRUCTION COST ESTIMATE SUMMARY

Item	Cost ($000)	
1. Processing Plant:		
• Site Preparation and Below Grade Foundations	1100	
• Above Grade Building with Auxiliaries	6947	
• Process Equipment	2743	
• Process Equipment Installation	1073	
• Electrical Equipment and Installation	1488	
Subtotal		13,351
2. Power Plant Facilities		
• Prime Construction Contract	4228	
• Windbox Modifications and Miscellaneous	272	
Subtotal		4,500
3. Engineering and Construction Supervision*		1,000
Total		18,851

* Estimated City costs only.

Processing Plant

Table 7 summarizes the Processing Plant Operating costs.

TABLE 7. SUMMARY OF ESTIMATED PROCESSING PLANT OPERATING COSTS - 236 Gg/y (260,000 TPY)

Item	$/year
Labor	815,000
Electric Power	354,000
Maintenance Supplies & Services	353,900
Miscellaneous Utilities	84,500
Residual Disposal	131,000
Total	1,638,400

Cost per Mg of Raw Refuse - $6.94
Cost per Ton of Raw Refuse - $6.30

Direct Labor is the largest item of operating costs. The summary of costs presented in this section is based on a detailed review of all probable job assignments related to the plant size and type and an anticipated operating schedule based on processing 907 Mg/d (1,000 TPD) of raw refuse in one 8-hour shift, 5 days per week. This will require that the majority of maintenance be accomplished on a second shift each of the operating days. Table 8 details the direct labor requirements and costs for the Processing Plant.

TABLE 8. PROCESSING PLANT DIRECT LABOR REQUIREMENTS AND COSTS

Direct Job Costs: Job Classification	Base Rate $/Year*	No. Personnel			$/Year
		1st Shift	2nd Shift	Total	
Plant Superintendent	22,750	1		1	22,750
Plant Engineer	18,000	1		1	18,000
Shift Supervisor	20,800	1	1	2	41,600
Process Operator	18,900	2		2	37,800
Sick Leave & Vacation Man	20,300	1		1	20,300
Front-Loader Operator	20,300	3		3	60,900
Traffic Director	14,500	1		1	14,500
Equipment Monitor	16,600	2		2	33,200
Laborer	12,600	3	2	5	63,000
Electrical Mechanic	21,000	1	1	2	42,000
Maintenance Mechanic	20,500	1	2	3	61,500
Janitor	10,400		1	1	10,400
Clerk/Stenographer	8,000	1	—	1	8,000
Subtotals		18	7	25	433,950
Other Labor Costs:					
Emergency overtime @ 7-1/2%					32,550
Labor Subtotal					466,500
Fringe Benefits and City Overhead @ 75% of Labor					350,000
TOTAL Labor Costs per Annum					816,500

Average Cost per Mg of Refuse------------------- $3.46
Average Cost per Ton of Refuse------------------ $3.14

* Wage rates are based on known City of Chicago rates for comparable job classifications adjusted to 1975 dollars.

Table 9 lists the various electrical loads connected with each processing line. The anticipated average demand at rated load is 2,525 kW per line. In addition, it is estimated that lighting and miscellaneous other equipment will average a demand of 700 kW while the plant is running and on the maintenance shift. The estimated demand at other times is 300 kW. On this basis, the electrical consumption per year will be 12,491,000 kWh, and the cost, at an average rate of $0.0283/kWh will be $354,000. The average electrical consumption per Mg of refuse processed is then 52.9 kWh at a cost of $1.50/Mg (48 kWh per ton at a cost of $1.36/ton).

In that a large maintenance staff is a part of the base payroll, the Maintenance Supplies and Services item only covers parts and special services, and is estimated at 1-1/4% of the purchase price of fixed mechanical equipment and 1% of building costs. In addition, a special cost of $0.44/Mg ($0.40/ton) of raw refuse processed is added for the rapid wearing parts of the shredders, such as the hammers, for an annual cost of $104,000. The percentage rate used on the mechanical equipment estimate is about half of the normal because of the low utilization rate of the equipment at 907 Mg/d (1,000 TPD) raw refuse processed.

The maintenance cost for the front loaders is calculated at 5% of the purchase price, or $9,000. In addition, it is assumed that this equipment will have to be replaced every 7 years. Therefore, a sinking fund payment of $21,100 is provided for. This fund is anticipated to earn compound interest at 6-1/2%.

TABLE 9. ELECTRICAL POWER LOADING PER PROCESSING LINE

Item	HP	Average Demand kW
1. Primary Feed Conveyor - Horizontal	10	6.9
- Inclined	20	13.8
2. Primary Shredder - Main	1000	718.1
- Lubpak	15	6.0
3. Primary Disch. Apron Conveyor	5	4.2
4. Coarse Disch. Belt Conveyor	20	16.0
5. Air Classifier - Vibrator Drive	30	22.4
- Air Blowers (2)	50	37.3
- Air Exhauster	250	176.1
6. Heavy Density Material Conveyor	5	4.0
7. Magnetic Separator Feeder	5	3.5
8. Magnetic Separator	5	3.5
9. Heavy Density Material Bin Power Pak	5	1.1
10. Fine Shredder - Main	1500	790.0
- Lubpak	5	3.0
11. Fine Shredder Discharge Conveyor	20	14.9
12. Pneumatic Pipeline Feeder	15	11.8
13. Pneumatic Pipeline Blower - Main	600	291.9
- Cooling Fan	2	1.7
14. Dust Collection		
- Tipping Floor Induction Fan	200	147.6
- Air Classifier Induction Fan	150	111.9
- Misc. Hoods Induction Fan	50	38.6
- Baghouse Drives (4)	50	35.0
- Air Locks to Dust Conveyor (6)	30	25.2
- Dust Conveying System	20	13.6
15. House Air Compressor	125	26.5
TOTAL	4187	2524.6

Within the Miscellaneous Utilities account is fuel for the front loaders estimated at $12,000; gas for heating ($0.71/GJ or $0.75/$10^6$ Btu) at $43,200; and water and sewer charges, plus telephone and miscellaneous supplies and services, at $30,000.

Residue Disposal cost is calculated on the basis of hauling at $0.17 per Mg-km ($0.25 per ton-mile) for a one-way trip of 11.3 km (7 miles) to the City-owned Stearns Quarry disposal site, plus costs at the quarry of $0.66/Mg ($0.60/ton). The total cost of residue disposal is estimated at $131,300.

Power Plant Facility

The complete costs of operating and maintaining the power plant facility are borne by Commonwealth Edison Company. Table 10 gives costs by in-plant category and by unit of refuse processed, as well as by heating value unit.

TABLE 10. SUMMARY OF OPERATING COSTS AT THE POWER PLANT FACILITY

Item	$/Year
Labor	129,800
Electric Power	106,200
Maintenance Labor & Supplies	118,000
Miscellaneous Utilities	8,000
TOTAL	362,000

Cost per Mg of Raw Refuse	$1.53
Cost per Ton of Raw Refuse	$1.39
Cost per GJ	$0.167
Cost per 10^6 Btu	$0.176

The system is highly mechanized and will be controlled from the boiler control center; it is anticipated that one man will be required to each shift continuously monitor the operation of both silos.

An extra shift of labor is provided each week at overtime rates in the event it is necessary to run into the weekend to consume all the fuel processed. In addition to this, it is expected that a laborer will be assigned to 1 shift per day for housekeeping purposes for a total of 4 men. Direct labor costs are then as follows:

3 Equipment Monitors @ $16,600	$ 49,800/yr.
1 Laborer @ $12,600	12,600/yr.
Subtotal	$ 62,400/yr.

1 shift/week Overtime	5,000
Fringe Benefits and Overhead @ 100%	62,400
TOTAL	$129,800/yr.
Cost per Mg of Raw Refuse	$0.55
Cost per Ton of Raw Refuse	$0.50

The average demand at the power plant site is 359 kW for the various blowers, fans, conveyors, drives, and lights. The estimated power consumption is 19.9 kWh/Mg (18.1 kWh per ton) of raw refuse processed, or 4,480,000 kWh/yr. The cost for electric power at an average of $0.0237/kWh is $106,200 per annum.

It is anticipated that maintenance will be conducted by the existing power plant maintenance department with additional staff added. Because the equipment will have a reasonably high usage factor, a maintenance cost of $118,000 has been estimated at 5% of the original cost on mechanical equipment and 1% on the silo building, including labor and supplies.

The Miscellaneous Utilities allowance of $8,000 is for expenses not covered elsewhere. There is no heating fuel requirement because the silo equipment room is heated by electric units. Water consumption is negligible. A typical expense would be the power plant share of the direct wire telephone connection to the processing plant control room.

REVENUES

Revenues to the City will be sale of recovered ferrous material and sale of fuel to the Commonwealth Edison Company. While the ferrous metal market fluctuates considerably, for estimating purposes the yearly income is considered to be $200,000. The original agreement with Commonwealth Edison Company, made before energy cost escalations, called for the utility to pay the city $0.30 per million Btu for the heating value of the RDF deposited in the silos. The system includes provision for weighing the incoming material and Edison plans on measuring heating value of the fuel periodically. The anticipated yearly revenue from this source, based on 2 167 TJ (2,053,000 x 10^6 Btu) delivered would be $616,000.

EXISTING PLANT COST SUMMARY

Costs of raw refuse disposal to the City of Chicago by the system is summarized in Table 11. Not included are costs borne by Commonwealth Edison Company, which are, of course, reflected in the fuel price.

EFFECT OF PRODUCTION RATE CHANGE

The preceding sections presented the costs for operating the plant at the rate of 907 Mg/d (1,000 TPD). The original design concept was predicated on a plant capable of processing a minimum of 1451 Mg/d (1,600 TPD) with a 100% processing equipment redundancy. The design described fulfills those criteria

TABLE 11. OVERALL COST SUMMARY - PRODUCTION RATE OF 907 Mg/d (1,000 TPD), 236 Gg/y (260,000 TPY)

Item	Annual Cost, $	$/Mg Raw Refuse	$/Ton Raw Refuse
Amortization:			
$18,851,000; 20 yrs @ 4.95%	1,506,000	6.38	5.79
Operating and Maintenance	1,638,000	6.94	6.30
Subtotal	3,144,000	13.32	12.09
Revenues:			
Ferrous - $200,000/yr.			
Fuel sales - $616,000/yr.	816,000	3.46	3.14
NET COST	2,328,000	9.86	8.95

by providing two identical processing lines, each capable of processing 1451 Mg/d (1,600 tons) of refuse at utilization rate of 83-1/3%. While one line is operating, maintenance can be performed on the other line. This would permit processing 377 Gg (416,000 tons) of raw refuse per year. It essentially means operating one line 20 hours per day 5 days per week. Table 12 summarizes the plant operating costs under these conditions.

TABLE 12. SUMMARY OF OPERATING COSTS AT PROCESSING RATE OF 1451 Mg/d (1,600 TPD), 377 Gg/y (416,000 TPY)

Item	$/Year
Labor	1,124,000
Electric Power	340,000
Maintenance Supplies and Services	363,000
Miscellaneous Utilities	109,000
Residue Disposal	210,000
Total	2,146,000
Cost per Mg of Raw Refuse . . . . $5.69 Cost per ton of Raw Refuse $5.16	

The direct labor requirements and costs are shown in Table 13.

TABLE 13. PROCESSING PLANT DIRECT LABOR REQUIREMENTS AND COST

	Base Rate $/Year	No. Personnel 1st Shift	2nd Shift	3rd Shift	Total	$/Year
Plant Superintendent	22,750	1			1	22,750
Plant Engineer	18,000	1	1	1	1	18,000
Shift Supervisor	20,800	1	1	1	3	62,400
Process Operator	18,900	1	1	1	3	56,700
Sick Leave & Vacation Man	20,300	1	1	*	2	40,600
Front-Loader Operator	20,300	2	1	1	4	81,200
Traffic Director	14,500	1			1	14,500
Equipment Monitor	16,600	3	2	2	7	49,800
Laborer	12,600	3	2	2	7	88,200
Electrical Mechanic	21,000	1	1	1	3	63,000
Maintenance Mechanic	20,500	1	1	1	3	61,500
Janitor	10,400		1		1	10,400
Clerk/Stenographer	8,000	1				8,000
Subtotals		15	12	8	34	597,350

Other Labor Costs:

Emergency Overtime @ 7-1/2%	44,800
Direct Labor Subtotal	642,150
Fringe Benefits and City Overhead @ 75% of Labor	481,612
Total Labor Costs per Annum	1,123,762

Average Cost/Mg of Refuse	$2.98
Average Cost/Ton of Refuse	$2.70

* 2 men float to cover 3 shifts.

The electric power requirement is 51.3 kWh/Mg (46.5 kWh/ton) for a total of 19,335,000 kWh/yr. The average cost is $0.0176/kWh for a total cost of $339,300 per annum. It is of interest to note that the power cost for this mode of operation is less than for processing 907 Mg/d (1,000 TPD) on a one shift per day basis. This is because when running one line vs. two, the demand charge portion of the power bill is reduced enough to more than offset the additional cost of the energy charge, which is all billed in a low cost block of the rate schedule.

Maintenance supplies would increase due to additional wear and tear and is estimated at $362,500/yr.

Miscellaneous utilities will increase because of increased heating costs resulting from operating the process line three shifts per day. Additional fuel will be required for the front-loaders, but other items will have negligible increases. The total is calculated at $109,000/yr.

Residue disposal will increase in direct proportion to the increased production to $210,000/yr.

Revenues will also increase in direct proportion to production, assuming a consumer is available. The overall cost summary is presented in Table 14.

TABLE 14. OVERALL COST SUMMARY - PRODUCTION RATE OF 1451 Mg/d OR 377 Gg/y (1,600 TPD, 416, 000 TPY)

Item	Annual Cost - $	$/Mg Raw Refuse	$/Ton Raw Refuse
Amortization: $18,851,000 for 20 yrs @ 4.95%	1,506,000	3.99	3.62
Operating and Maintenance	2,146,000	5.69	5.16
Subtotal	3,652,000	9.68	8.78
Revenues:			
Ferrous $320,000			
Fuel Sales 986,000	1,306,000	3.46	3.14
NET COST	2,346,000	6.22	5.64

ENVIRONMENTAL CONSIDERATIONS

Within the supplementary fuel processing facility itself, environmental effects can result from atmospheric emissions, water effluent, and noise. None of these are anticipated to create any particular problems not solvable within the existing design or with minor modifications to it.

All refuse placed on the tipping floor is processed continuously and none remains in excess of 8 hours. In the event of any downstream processing malfunctions, city trucks will remove the material to alternative disposal sites. Anaerobic digestion of the wastes to odoriferous compounds is limited because of the short duration of open exposure and the rather high degree of air contact with the low density material. The temporary storage area is under a slightly negative pressure, with all air being ultimately exhausted through a baghouse fabric filter system. Similar filter systems collect all dust from hoods at critical areas of the processing equipment. All baghouse dust is periodically introduced into the supplementary fuel transport line for combustion in the Commonwealth Edison furnaces.

Operating experience must be gained as to the extent of water contamination resulting from plant operations. The design incorporates a package treatment unit for removal of scum and suspended solids prior to introduction of the clear effluent to the sewer system. The level of soluble BOD contamination of this water is not known at this time. Other package treatment units could further reduce the organic level if this proves necessary.

Noises generated by conveyors, fans, and shredders are contained within the building structure. The highest noise generators are the shredders (2 primary and 2 secondary), located in a room separated from the main receiving area by a heavy concrete wall. The room is large so that noise is diffused to a great extent. When maintenance is performed while a shredder is in operation, workers wear prescribed noise-reducing ear muffs. The shredders are of especially heavy construction, both in body and covered hood, thus transmitting less noise than usually found with size reduction equipment. Otherwise, little is transmitted to the receiving area and will be less than 66 dB(A) at the property boundaries as required by the City of Chicago Heavy Manufacturing District Zone code.

Noise from air compressors for the pneumatic system is led through a silencer to prevent noise transmission through the air inlet. The shredded material in the transport pipe also absorbs the sound and the air finally exits through cyclones and baghouses that also reduce the sound to acceptable levels.

Truck noise on the receiving floor is contained within the building. Conveyor noises are essentially low and contained in the building.

Environmental considerations at the power plant site are similar to other facilities designed to store, transport, and burn RDF. Principal experience has been gained at St. Louis, where rather extensive testing has demonstrated no undue changes in effluents occur over combustion of 100% coal in modern furnaces. Further tests must be conducted to establish the exact extent of emissions and the best control technology to employ and no such tests have yet been made at Chicago. The St. Louis data (Refs. 8 and 9), taken at RDF firing rates varying up to 27 percent on a power output basis, indicate no statistically significant changes in NO_x or SO_x emissions. Average emission of chlorides, for which there are no local or federal air quality standards, was approximately 30 percent higher during combined firing operations in the 125 MW furnace. Samples for particulate matter examination were taken both before and after the 97.5 percent efficient electrostatic precipitator. Upstream of the precipitator, in terms of mass of particulates per unit boiler heat input, there was no change in particle loading when RDF was added to the furnace. Downstream, no change occurred up to the design capacity of the boiler. Above 125 MW, however, particulates increased with combined firing. The data cannot be fully explained yet, although several theories have been developed and solutions suggested if a utility might desire to operate above design stream output levels.

Shredded combustibles will not be stored more than two days at the power plant. Experience at Madison, Wisconsin, and St. Louis indicate that no odors should develop during this time.

SECTION 6

GEORGIA INSTITUTE OF TECHNOLOGY MOBILE AGRICULTURAL PYROLYSIS SYSTEM

INTRODUCTION AND SUMMARY

The Georgia Tech Engineering Experiment Station (EES) has been conducting R & D on an air-blown pyrolysis converter for agricultural wastes. The EES group has proposed that equipment for processing 182 Mg/d (200 TPD) of wet wastes into 40.9 Mg (45 ton) of a char-oil fuel mixture could be contained on two standard highway trailers and thus could offer the potential for moving from source to source of waste on a periodic basis. Design operating conditions were selected from a limited number of experiments from pilot units at the EES processing 22.7 and 5.5 dry Mg/d (25 and 6 TPD). The developers prepared equipment listings, suggested a suitable configurational layout, and derived cost estimates for the proposed mobile system. As the most developmental system in the group of candidates, the mobile pyrolysis plant could only be examined on a rather conceptual basis by Parsons. The experimental results appear entirely reasonable when compared to similar pyrolysis studies and have been accepted as the basis for a system that is reviewed here. Design comments are made and probable costs for a single system and lots of 100 have been estimated by Parsons specialists.

CONCLUSIONS

- The EES agricultural pyrolysis system is the least developed of the candidates analyzed here. While only limited experimental tests have been made on which energy and material balances can be based, cellulosic pyrolysis chemistry is sufficiently well understood to conclude the proposed system is technologically sound. R&D remaining to be conducted will primarily help establish the economics of the mobile concept, while also increasing knowledge of properties of the fuel to be produced. If practical hardware can be assembled economically, the system should prove of great merit in converting farm-related waste materials to energy.

- It is recommended that component-level scale-up testing be accomplished prior to building a two or three trailer prototype unit. The latter effort would be a rather straight forward construction task once further R&D demonstrates necessary design features to be used. The following components require study:

    - Waste Dryer - Equipment for evaporating water from natural products is designed on an empirical basis. The dryer would be the largest item in the system and its performance and energy needs must be determined with a full size unit.

- Pyrolysis Converter - The pilot plant pyrolysis equipment was intended to yield information on the quantities of gas, liquid, and char resulting from waste decomposition under varying conditions. Scale-up and incorporation of realistic engineering features can reveal problems that must be studied with an essentially full size unit. A waste introduction device, stirrer/air introduction equipment, insulation, product condenser, and bottom char release unit all need to be investigated.

- Combustor - The efficiency and performance of a commercial or custom combustor for producing the hot drying gas must be established.

- Power Generator - Moderately extensive use of the off-gas as a fuel for an internal combustion engine should be conducted to establish power output and effects on engine maintenance.

- The Parsons' design review is unable to verify the suggested performance capability of the Georgia Tech dryer. While the art of drying of natural products is quite empirical and very dependent on particle size distribution of the product to be dried, conventional commercial equipment is much larger than the unit recommended. A third trailer will be required if even a slightly larger dryer than suggested by the EES staff proves necessary.

- Possible problems with the blending of the pyrolytic oil with the char have not yet been well established. It would be essential to assure that no possible fire results upon mixing and thus adequate cooling of the low thermal conductivity char would be required. The chars produced from varying waste sources might each demand different blending techniques to assure oil incorporation and lack of balling or smearing of the mixed product. Analysis of this problem leads to the conclusion that perhaps blending should only be utilized in those rare cases where no market outlet exists for the liquid fraction. This latter fraction has approximately the same heating value as the char and net energy yield varies little with the ratio of liquid to solid. Economically, however, the oil is valued at several times that of the solid on a unit heating value basis, and hence its isolation and separate sale should be considered.

PROCESS DESCRIPTION

Overview

The basic processing scheme utilized in the ESS waste-to-energy system is similar to that used in the PUROX and TORRAX reactors. Cellulosic waste continuously passes downward through a vertical shaft converter, where it is first dried, then thermally degraded in a pyrolysis zone heated by upward moving gases leaving the bottom combustion zone. In this latter zone, air is used to oxidize a portion of the char remaining after the waste has been decomposed to gaseous and liquid products. The gas, being diluted with nitrogen from the air, has a rather low volumetric heating value, but its energy is fully utilized by (1) burning it within an internal combustion engine that in turn powers an electrical generator and (2) within an air-gas combustor whose hot exhaust gases are used as the heating fluid for partially drying the raw waste. The solid char and liquid products have very good heating values and may be used as fuels in systems normally using coal or fuel oil. The oil may be incorporated into the char whenever a single fuel product is desired.

The overall process thus converts a low density, low heating value, waste into valuable fuel that can be economically transported to energy consumers. An important concept of the EES system is the ability of the processing plant to move to the many sources of waste, rather than vice versa, with probable significant advantages in transportation costs in many farming areas.

Detailed operational characteristics of the processes are best examined through review of the two principal experimental units used at the EES. This equipment is described and the research data presented in the final reports for the EPA-supported investigations under Contract 68-02-1485 and Grant R803430-01-0 and in the publications cited as References 10, 11, and 12.

R & D Facilities--

A simplified flow diagram for both units is shown in Figure 12. The outside dimensions of the 5.2 Mg/d (6 TPD) unit are 3 m (10 ft) tall by 1.2 m (4 ft) on each side, with the inside dimensions being 1.2 m (4 ft) deep by 0.6 x 0.6 m (2 x 2 ft). The 22.7 Mg/d (25 TPD) pyrolyzer is 5.5 m (18 ft) tall and 1.8 m (6 ft) on each side, with inside dimensions of 2.4 m (8 ft) in depth with a 1.2 m (4 ft) diameter cylinder.

Feed (moderately pulverized) enters the top of the converter through a valve and falls onto the top of the bed. Towards the lower portion of this bed are water-cooled tubes for introduction of combustion air into the reactor. Only the amount of oxidation of a portion of the char is permitted to occur that will supply sufficient hot gases for the decomposition of the feed material in the intermediate section of the bed. Operating pressure is maintained at several inches water column below atmospheric in the large unit and several inches above in the small one. As the 427 to 704°C (800 to 1300°F) gases pass over the waste material, decomposition and rearrangement reactions occur, yielding gaseous, liquid, and solid (char) products. The latter pass out through a mechanical output system and the char is then further transported by means of a screw conveyor.

The warm gas and aerosols pass upward through the downward moving bed into mechanical separators and then a liquid fraction is isolated in an air-cooled condenser. Temperature is adjusted so that water is not permitted to condense. The off gas is combusted with air and vented during R & D tests, but would be utilized to dry incoming feed and to generate required process power in the contemplated large mobile system.

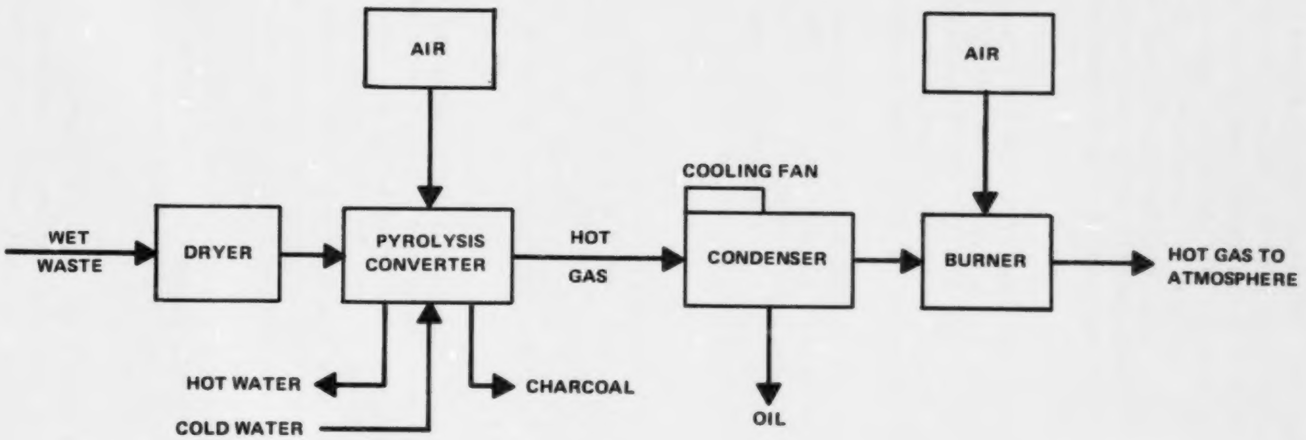

AIR
AIR
COOLING FAN
WET
WASTE
DRYER
PYROLYSIS
CONVERTER
HOT
GAS
CONDENSER
BURNER
HOT GAS TO
ATMOSPHERE
HOT WATER
CHARCOAL
COLD WATER
OIL

Figure 12. Process flow diagram of EES research unit.

Various bed stirring and agitation devices have been studied. In the latter phases of testing, an L-shaped water-cooled stirrer that also introduced the combustion air was employed. This device has been named the "AIRGITATOR" by the EES development group. Air delivery by it is through 1.6 mm (0.062 in.) holes spaced 12.7 mm (0.5 in.) apart.

Research Results

Because of the difficulty of maintaining constant conditions within the pilot plant units and establishing accurate mass balance information, laboratory tests have been made to better determine the general trend of product yields. This work, described in Reference 10, was conducted with sawdust samples on the order of 2.5 kg (5.5 lb) that had been dried to a 6 percent water level. The HHV was 18.85 MJ/kg (8103 Btu/lb). Samples were contained within a stainless steel tube leading to collection traps and were heated by an external furnace maintained at temperatures between 540 and 870°C (1004 and 1598°F). Because the time--temperature history of initial solid particles and decomposition products is different than occurs in a large vertical shaft convertor, and because of the absence of air, results cannot be directly used for design purposes. Excellent guidelines for predicting probable results in production equipment are obtained from this work, however.

In Figure 13 the yields of gas, char, water, and oil are shown as a function of temperature, with the upper total product line indicating good experimental recovery was achieved. The trends are rather typical of results obtained by other investigators.

Changes in composition of the gas fraction as a function of the temperature to which the sample was subjected are shown in Figure 14. Calculations of heating values from these curves show a linear increase from 14.37 MJ/Nm^3 (365 Btu/SCF) at 540°C (1004°F) to 16.54 MJ/Nm^3 (420 Btu/SCF) at 760°C (1400°F) and then a slight decrease at the highest furnace temperature.

Heat of combustion of the oil and char was measured in the laboratory. For the liquid fraction, results vary (water-free basis) from 27.91 to 32.56 MJ/kg (12,000 to 14,000 Btu/lb). The solid had a quite constant heating value, averaging 33.18 MJ/kg (14,267 Btu/lb). From these data, the heating values of the individual fractions of the products as a function of temperature have been plotted in Figure 15. The important fact to be noted here is that the sum essentially equals the original energy content of the dry waste, demonstrating that little loss need occur in such a pyrolysis system. In the practical case, the heat represented by the electric furnace must be supplied by a portion of the waste, but with properly designed equipment, overall energy conversion efficiencies can be in the range of 60 to 70%.

Test results in the pilot units with wood feed are shown in Table 15 and with peanut hull feed in Table 16. From the results of the experimental work, it was concluded that:

- The effects of the air/feed ratio on product energy yields appear to be dominant; changing size and feed material, and the effects of

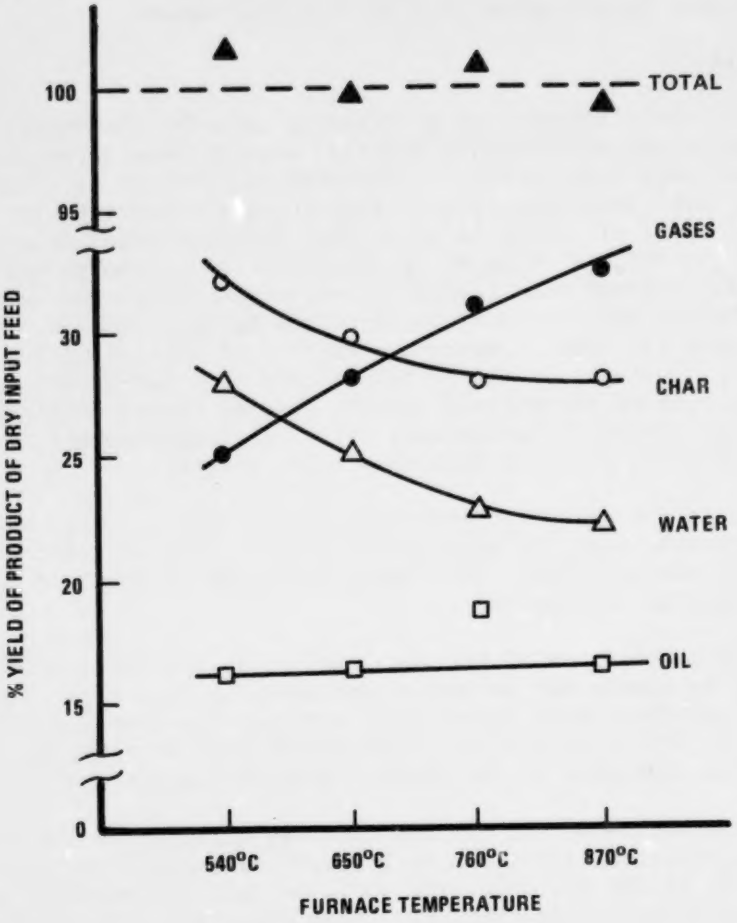


Figure 13. Pyrolytic product yields from laboratory tests.

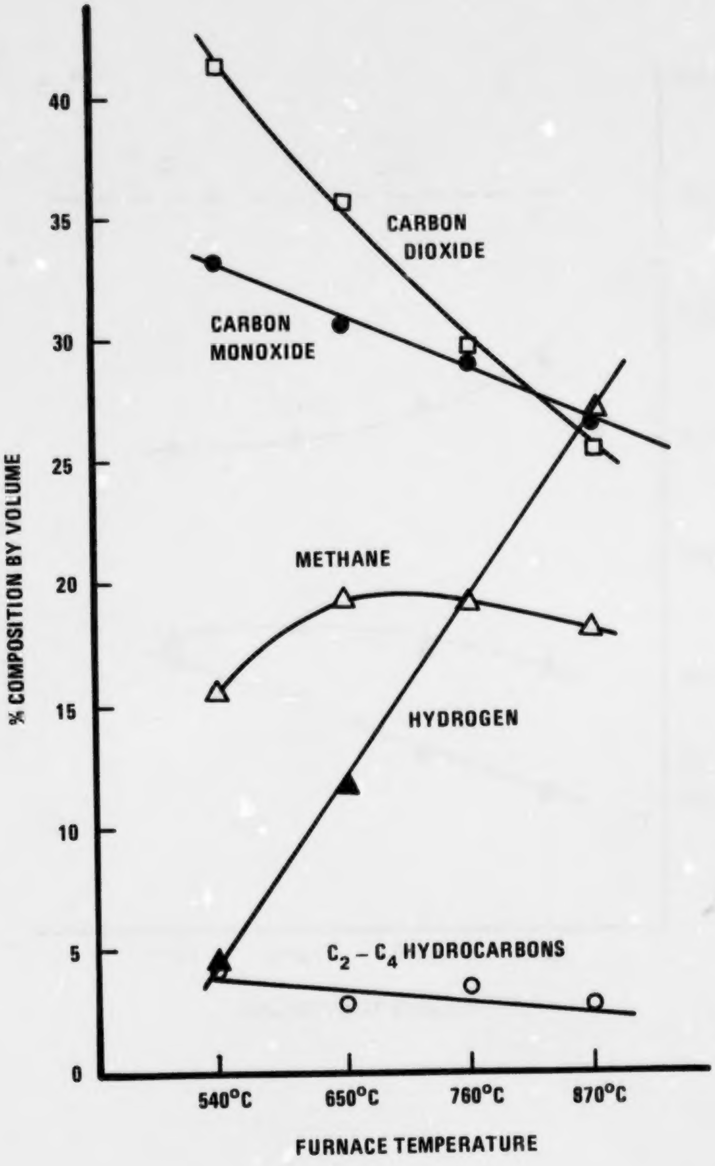


Figure 14. Gas fraction composition as a function of temperature.

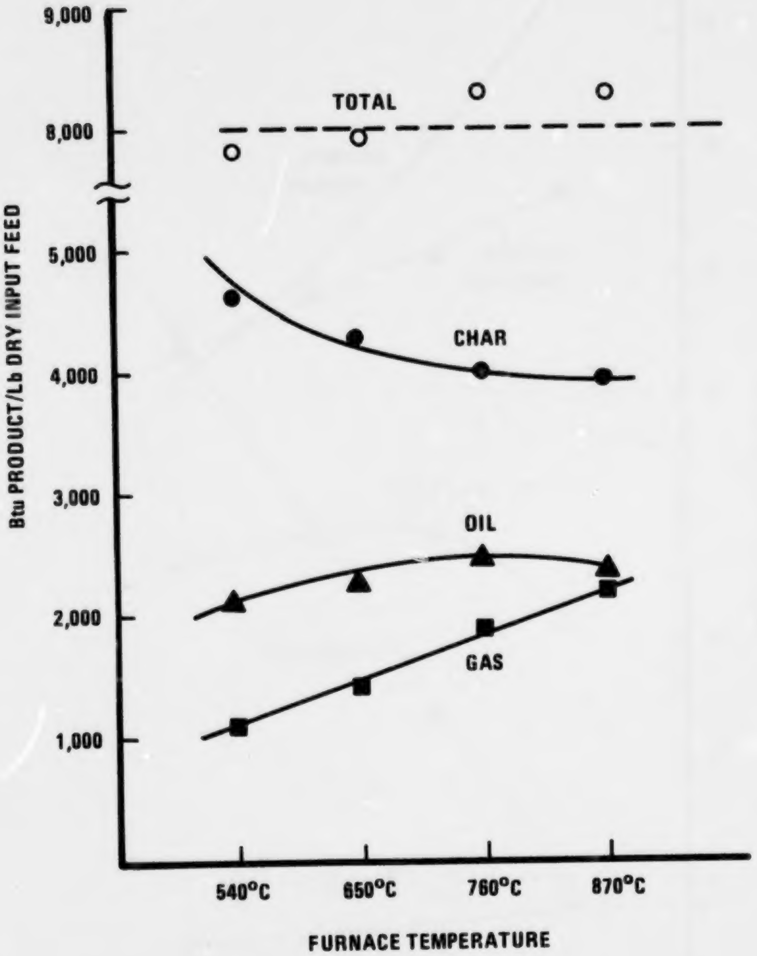


Figure 15. Heating values of product fractions as a function of temperature.

TABLE 15. SUMMARY OF TEST RESULTS WITH WOOD FEED

Run No.	Air/ Feed (Wgt. ratio)	Feed Rate kg/h	Feed Rate lb/hr	Char* Yield kg	Char* Yield lb	Oil* Yield kg	Oil* Yield lb	Lost* Carbon kg	Lost* Carbon lb	Mass Output/ Input	Energy Output/ Input	Available** Energy (Percent)	Comments
4	0.474	132	291	8.5	18.7	2.9	6.3	7.7	17.0	1.02	0.947	65.1	No agitation
5	0.531	112	246	9.4	20.7	3.0	6.7	4.8	10.6	1.02	0.918	58.2	Agitation
9	0.704	83	184	5.3	11.6	6.5	14.4	3.3	7.2	0.94	0.995	58.8	No agitation
10	0.638	83	184	4.7	10.4	5.1	11.3	6.2	13.6	0.98	0.968	62.1	Agitation
17	0.382	88	195	12.7	28.1	3.7	8.1	5.8	12.9	0.98	0.936	72.5	No agitation
18	0.580	86	189	4.6	10.2	5.1	11.3	5.6	12.3	0.99	0.946	58.4	No agitation
19	0.416	84	186	12.6	27.8	6.5	14.3	0.4	0.8	0.91	0.923	65.6	O_2 balance not good. No agitation
6	0.272	223	491	11.7	25.8	3.5	7.8	3.4	7.4	1.03	0.966	67.7	Significant loss of oil from the condenser. No agitation
7	0.558	92	202	7.3	16.1	4.8	10.7	0.9	2.1	0.95	0.939	50.6	Agitation
8	0.349	102	226	10.2	22.5	5.4	12.0	3.8	8.4	0.98	0.968	47.7	No agitation
12	0.453	107	237	11.9	26.3	2.7	5.9	1.9	4.3	1.05	0.905	60.1	O_2 balance not good. No agitation
13	0.378	53	118	13.1	28.9	6.8	15.0	0.8	1.7	0.96	0.990	74.9	Oil condensing caused erratic flow. No agitation
15	0.220	157	346	14.7	32.4	5.5	12.1	2.7	5.9	0.97	1.004	78.3	No agitation
16	0.492	101	222	7.9	17.4	6.2	13.8	3.5	7.8	0.98	0.977	65.4	No agitation

* All results are presented on a basis of 100 lb dry sawdust.

**Energy available in char/oil divided by total available from sawdust feed.

General notes: (a) Bed depth of first two runs was 46 cm (18 in.): next five 69 cm (27 in.)· remainder at 99 cm (39 in.)
(b) All tests with 2 air tubes except first two with 4 and next three with 3.

TABLE 16. SUMMARY OF TEST RESULTS, PEANUT HULL FEED

Test No.	Feed	Feed Rate		% Char Yield	% Oil & Aqueous Yield	Air/Feed (Wgt. ratio)	Off-Gas Temp		Bed Depth		Agitation	Airgitation
		kg/h	lb/hr				°C	°F	cm	in.		
1	Peanut Hulls	571	1260	21.7	3.9	0.364	97	207	132	52	No	No
2	Peanut Hulls	390	859	23.9	8.5	0.265	93	200	132	52	No	No
3	Pin Sawdust	676	1490	26.6	5.7	0.172	113	235	132	52	No	No
4	Pine Sawdust	464	1022	24.9	7.0	0.251	141	285	132	52	Yes	No
5	Peanut Hulls	494	1090	28.8	7.9	0.227	87	188	132	52	Yes	No
6	Peanut Hulls	481	1060	32.1	7.2	0.227	86	186	132	52	Yes	No
7	Peanut Hulls	476	1050	22.9	4.7	0.270	88	190	132	52	Yes	No
8				CHECK OUT "AIRGITATOR"							No	Yes
9	Peanut Hulls	408	900	40.0	16.1	0.458	79	174	89	35	Yes	No
10	Peanut Hulls	501	1105	24.9	4.53	0.464	88	190	89	35	Yes	No
11	Peanut Hulls	570	1257	27.0	23.4	0.539	87	188	89	35	Yes	No
12	Peanut Hulls	471	1038	28.4	17.8	0.613	83	182	89	35	Yes	No
13				CHECK OUT MODIFIED "AIRGITATOR"							No	Yes
14	Peanut Hulls	490	1080	41.4	3.5	0.140	174	345	127	50	No	Yes
15	Peanut Hulls	324	715	28.3	26.2	0.190	227	440	127	50	No	Yes

mechanical agitation, are of minor importance compared with the air/feed ratio.

- The available energy in the char-oil mixture appears to be a single function of the air/feed ratio.
- While the total energy in the char-oil mixture is a function only of the air/feed ratio, the relative amounts of char and oil can be changed significantly by varying the bed depth.
- The integrated mechanical agitation-air supply system, or "AIRGITATOR," appears to offer advantages of increased through-put, operating stability, and off-gas temperature at very low values of the air/feed ratio.
- The overall mass, energy, and chemical balances appear to be reasonable and satisfactory.

In that a gaseous fuel has little application as a product in the mobile concept, and because gas yields increase with temperature, relatively low pyrolytic temperatures should be selected for maximum energy yields, consistent with suitable rapid reaction rates. Selection of the proper air/feed ratio, the controlling factor for temperature, therefore becomes the most critical design factor for practical hardware.

The EES method of selection of the proper air/feed ratio operating point is a graphical one as represented in Figure 16, the bases of which are the experimentally observed compositional values from the pilot units. The curve in the upper right quadrant represents heat consumed in the process, consisting of 3.49 MJ/kg (1,500 Btu/lb) to evaporate water from the original feed stock and 0.84 MJ/kg (360 Btu/lb) to process the dry feed. In the example illustrated, it is assumed that an agricultural waste containing 50% water (a rather typical value) is fed to the dryer. To supply the required 4.33 MJ/kg (1,860 Btu/lb) of dry feed, an air/feed ratio of 0.47 would yield an off-gas having this quantity of heat. The remaining char and oil would have a summed heating value of 12.79 MJ/kg (5,500 Btu/lb) of dry feed, for a process thermal efficiency of about 65 percent. For wastes having different original moisture contents, other air/feed ratios would be utilized, it being apparent that there are significant advantages in starting with a low water content waste.

The 50% water content control point has been used in all design analysis by Parsons.

MOBILE PYROLYSIS SYSTEM CONCEPT

Sufficient testing was accomplished with the pilot units to ascertain the nature of the important process variables and the probable net energy yields when agricultural wastes are used as a feedstock. The EES process developers then proceeded to develop a preliminary design for a transportable facility capable of producing pyrolytic char and oil fuel from stockpiles of waste

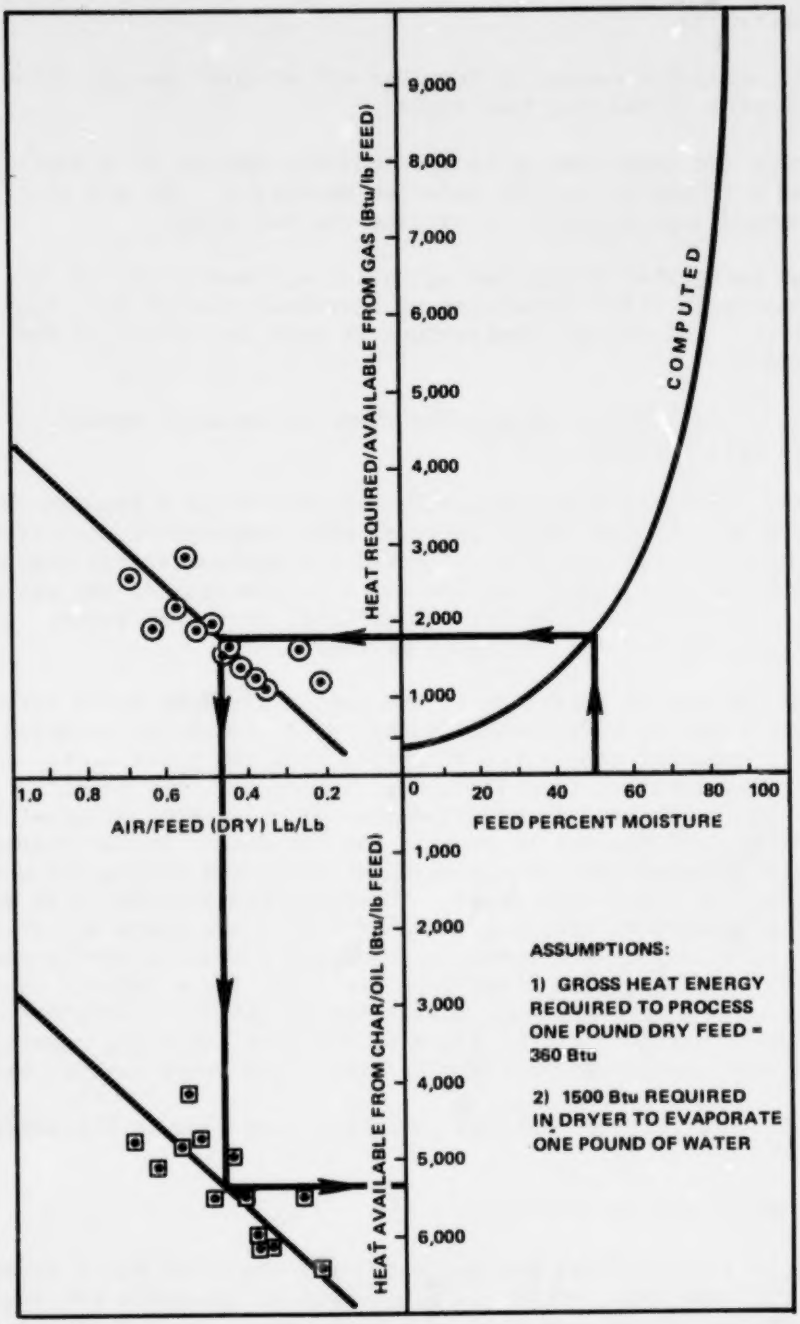


Figure 16. Selection of air/feed ratio.

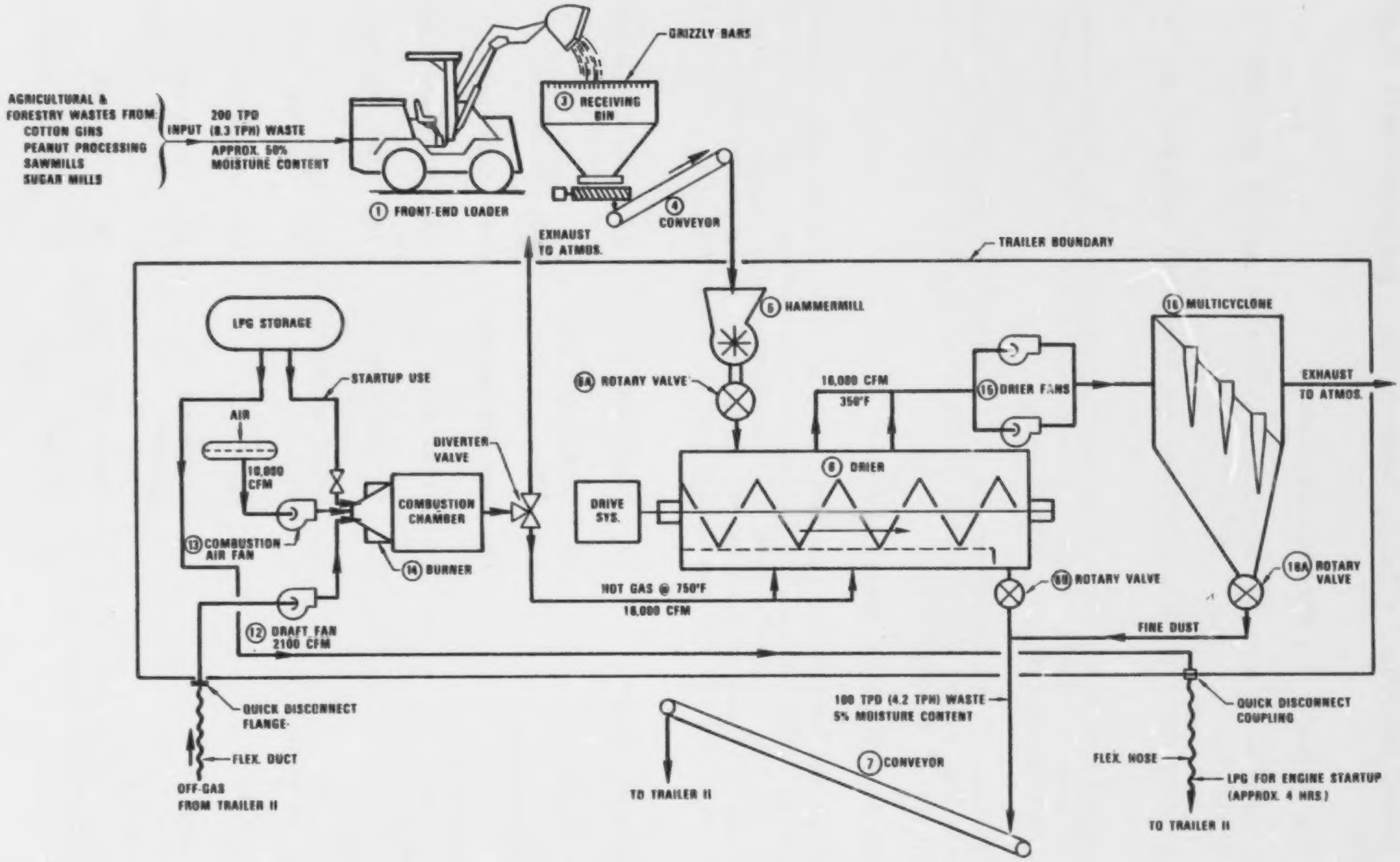
materials located throughout a fairly large region. Design criteria they selected were:

- No requirements for external utilities.
- Full compliance with all applicable pollution control and OSHA regulations.
- Processing capacity of 200 tons of wet fuel (50% moisture) per 24-hour day.
- Capability of being carried on two trailers having maximum dimensions of 55 feet in length, 8 feet in width, 13-1/2 feet in height, and weighing no more than 73,000 lb each.
- Insulation of the converter could be accomplished by means of small inside shelves to contain char produced within the reactor (and self-regenerated as required).

DESIGN REVIEW OF CONCEPTUAL MOBILE SYSTEM

Figures 17 and 18 present the basic process flow diagram of the mobile pyrolysis system suggested by EES, in one possible configuration they have proposed for the two-trailer system. The equipment list numbering system is that of EES and has been adopted in this section to avoid any confusion between the original work and the Parsons design review. That original listing is as follows:

1. Front end loader
2. Bin conveyor
3. Receiving bin
4. Conveyor mill
5. Hammer mill
6. Drier
7. Feed conveyor
8. Converter
9. Cyclone
10. Condenser
11. Condenser cooling fan
12. Draft fan
13. Combustion air fan
14. Off-gas burner
15. Drier fans
16. Burner exhaust
17. Drier exhaust duct
18. Cyclone
19. Process air blower
20. Generator
21. Engine
22. Cooling water radiator
23. Compressor
24. Conveyor
25. Char oil mixer
26. Char storage bin
27. Control room
28. Agitator
29. Front end loader storage
30. Cat walk
31. Engine blower



AGRICULTURAL &
FORESTRY WASTES FROM:
COTTON GINS
PEANUT PROCESSING
SAWMILLS
SUGAR MILLS
INPUT
200 TPD
(8.3 TPH) WASTE
APPROX. 50%
MOISTURE CONTENT
① FRONT-END LOADER
GRIZZLY BARS
③ RECEIVING BIN
④ CONVEYOR
EXHAUST
TO ATMOS.
TRAILER BOUNDARY
⑤ HAMMERMILL
6A ROTARY VALVE
⑯ MULTICYCLONE
LPG STORAGE
STARTUP USE
AIR
10,000 CFM
⑬ COMBUSTION AIR FAN
⑭ BURNER
COMBUSTION CHAMBER
DIVERTER VALVE
DRIVE SYS.
⑥ DRIER
16,000 CFM
350°F
⑮ DRIER FANS
EXHAUST
TO ATMOS.
HOT GAS @ 750°F
16,000 CFM
6B ROTARY VALVE
16A ROTARY VALVE
FINE DUST
⑫ DRAFT FAN
2100 CFM
QUICK DISCONNECT FLANGE
FLEX. DUCT
OFF-GAS
FROM TRAILER II
TO TRAILER II
⑦ CONVEYOR
100 TPD (4.2 TPH) WASTE
5% MOISTURE CONTENT
QUICK DISCONNECT COUPLING
FLEX. HOSE
LPG FOR ENGINE STARTUP
(APPROX. 4 HRS.)
TO TRAILER II

Figure 17. Process flow diagram trailer No. I.

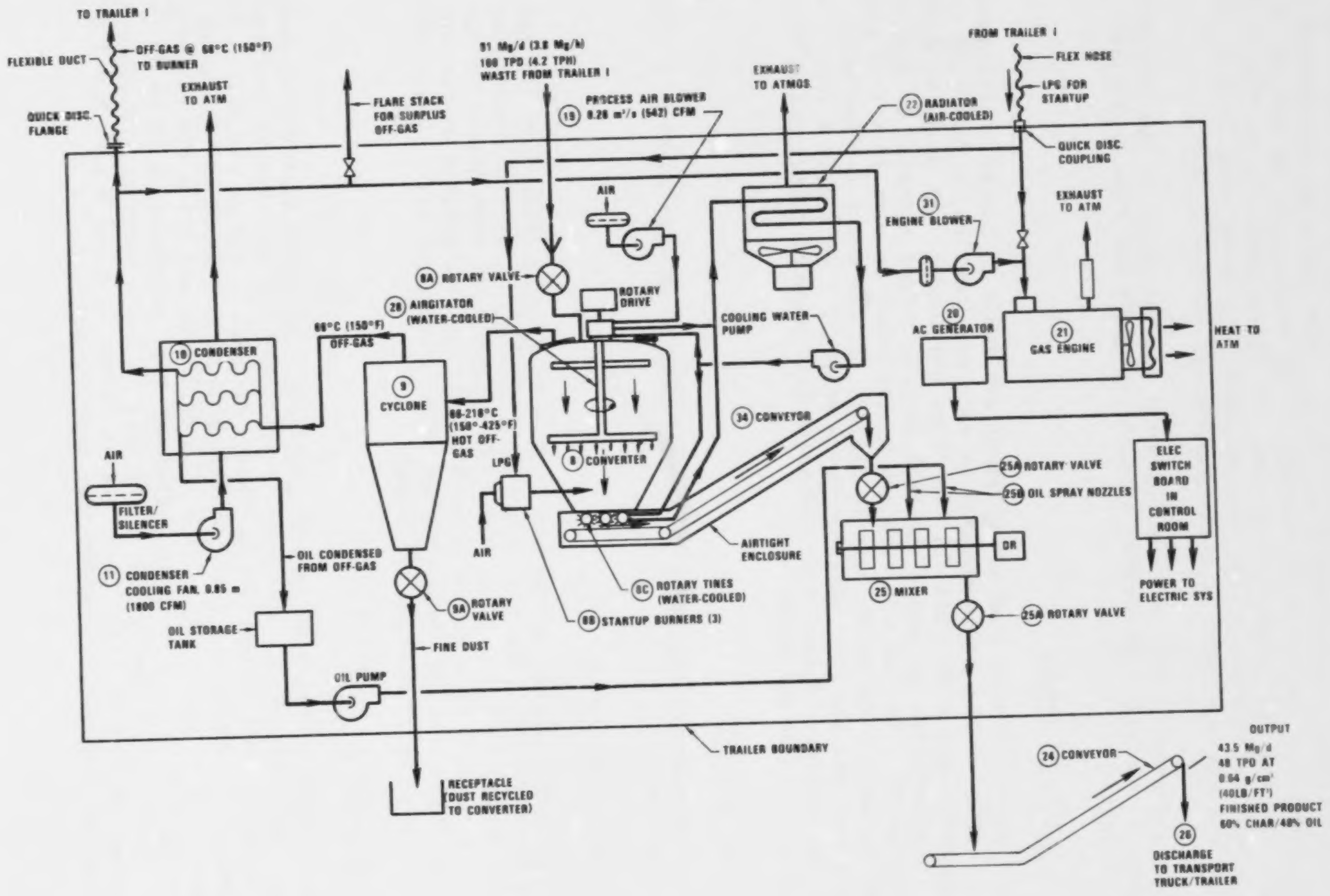

TO TRAILER I
FLEXIBLE DUCT
OFF-GAS @ 66°C (150°F) TO BURNER
QUICK DISC. FLANGE
EXHAUST TO ATM
FLARE STACK FOR SURPLUS OFF-GAS
91 Mg/d (3.8 Mg/h) 100 TPD (4.2 TPH) WASTE FROM TRAILER I
19 PROCESS AIR BLOWER 0.26 m³/s (542) CFM
EXHAUST TO ATMOS.
22 RADIATOR (AIR-COOLED)
FROM TRAILER I
FLEX HOSE
LPG FOR STARTUP
QUICK DISC. COUPLING
AIR
31 ENGINE BLOWER
EXHAUST TO ATM
8A ROTARY VALVE
ROTARY DRIVE
28 AIRGITATOR (WATER-COOLED)
66°C (150°F) OFF-GAS
COOLING WATER PUMP
20 AC GENERATOR
21 GAS ENGINE
HEAT TO ATM
10 CONDENSER
9 CYCLONE
66-218°C (150°-425°F) HOT OFF-GAS
34 CONVEYOR
LPG
8 CONVERTER
25A ROTARY VALVE
25B OIL SPRAY NOZZLES
ELEC SWITCH BOARD IN CONTROL ROOM
AIR
FILTER/ SILENCER
AIR
AIRTIGHT ENCLOSURE
DR
11 CONDENSER COOLING FAN. 0.85 m (1800 CFM)
OIL CONDENSED FROM OFF-GAS
9A ROTARY VALVE
8C ROTARY TINES (WATER-COOLED)
8B STARTUP BURNERS (3)
25 MIXER
POWER TO ELECTRIC SYS
OIL STORAGE TANK
FINE DUST
25A ROTARY VALVE
OIL PUMP
TRAILER BOUNDARY
OUTPUT
43.5 Mg/d 48 TPD AT 0.64 g/cm³ (40LB/FT³) FINISHED PRODUCT 60% CHAR/40% OIL
24 CONVEYOR
26 DISCHARGE TO TRANSPORT TRUCK/TRAILER
RECEPTACLE (DUST RECYCLED TO CONVERTER)

Figure 18. Process flow diagram of trailer No. II.

At the current state of development and from any evidence submitted to Parsons for review, a high probability exists that the dryer recommended by EES is insufficient in volume to accomplish the desired drying down to 5% moisture. If the best commercially available agricultural dryer must be used in its place, a third processing trailer would have to be used in order to transport all the equipment to fully process 181 Mg/d (200 TPD).

Each sub-section that follows discusses the functions of the equipment and presents comments from vendors of such equipment and from specialists within Parsons.

Item 1 - Front End Loader

In order to have an item of equipment available to assist in the assembly and disassembly of the process system at each new location, a fork lift truck is recommended as a substitute for the front end loader. It would be equipped with a scoop attached to handle the bulk wastes, either manually or hydraulically controlled. The 5000-lb capacity Hyster Model 50 with 14 x 17.5 tires would be suitable. Its basic cost is $16,000 ($2,000 extra for hydraulic scoop control) and the unit would occupy a space of 1.68 x 3.05 m (66 x 120 in.) on the trailer. Manually or hydraulically operated runway rails for on/off loading would be required.

Item 2 - Bin Conveyor

It is recommended that this item be eliminated and the waste be placed directly in the bin.

Item 3 - Receiving Bin

The estimated weight of the bin is 2.04 to 2.27 Mg (4500-5000 lb) and is one item for which the fork lift would be a necessity (lifting brackets or lugs would be 2.1 to 2.4 m (7 to 8 ft) off ground level when stowed on the trailer). A grizzly (coarse bar screen) should be incorporated on the top to assure that large foreign objects do not enter the hammer mill. Three vendors submitted prices between $1656 and $2500.

Item 4 - Conveyor to Mill

The conveyor presents no special problems. Its speed should preferably be automatically controlled to prevent overloading the mill and an overhead magnet should be used to remove tramp metal that could damage the mill. The Valley Industrial Supply Co. inclined belt conveyor at $1500 is typical of those that could be used. It is 30 cm (12 in.) wide and 6.1 m (20 ft) long and is equipped with a 10 cm (4 in.) diameter tail pulley and a 20 cm (8 in.) diameter rubber lagged head pulley. The belt is 3-ply Neoprene, reinforced with 12 gauge galvanized steel bead, and is driven by a 560 W (3/4 H.P.) motor. Other prices of from $1628 to $4000 have been obtained.

Item 5 - Hammer Mill

The Gruendler model 30-2 56 kW (75 HP) mill is recommended over the Williams C-32 suggested by the developers. It has a more compact design and a lower weight. Current price is $12,750. Vibration of the mill could create some problems with items mounted on Trailer No. I; this should be investigated before a final production design is completed. A rotary feeder should be incorporated between the mill and the dryer to prevent blow-by.

Item 6 - Dryer

The dryer is one of the major components in the pyrolysis system that requires further investigation and testing at the full scale component level. The dryer depicted in the EES concept sketches is a modification of an experimental dryer developed by the Tech-Air Corporation of Atlanta. A unit of this type was in operation at Cordele, Georgia, drying hogged wood waste at the time of preparation of this report, but detailed performance data could not be released to Parsons. Such data should be sought for release prior to any final design of the mobile system. None of the drying equipment manufacturers contacted are able to supply a unit of the type depicted in the EES concept sketches or that will meet the necessary space constraints. Based on their dryer performance experience, several manufacturers have considerable doubt that a dryer of this design, type, and dimensions could meet the required performance. Most manufacturers recommended a rotary drum type; these are well over 2.4 m (8 ft) in diameter to adequately dry typical agricultural materials. One organization proposed a fluidized bed type that was quite tall and would have to be folded down for transport. Another company has a combined hammer mill and vertical dryer, but it is over 7.6 m (25 ft) tall.

Generally, it is the belief of commercial dryer manufacturers and of Parsons that the EES concept dryer would not provide sufficient intimate contact between the moist feed material and the hot drying air. A tumbling action is needed to break up clumps of material and expose the surfaces of the particles to the drying air. This is necessary because of the thermal insulating properties of the feed material and the inherently slow diffusion of the physically bound water to the surface of the particle. Without sufficient aeration, the drying time is increased, resulting in the larger sized unit.

The EES dryer concept consists of a 91-cm (36 in.) diameter helical screw having some paddle arms to produce a mixing and tumbling action in the material. The screw moves the moist feed material horizontally along a perforated trough in the same manner as a screw conveyor functions. Hot drying air under a slight pressure is forced up through the perforations from the plenum located below the trough. This action is similar to the action in a fluid bed. Reportedly, the dryer removes moisture in the feed material from an initial 50 percent to 5 percent total moisture content using hot gas having an inlet temperature of approximately 371°C (700°F), and 430 m^3/min. (16,000 CFM) gas flow. The dryer should be constructed of stainless steel to preclude oxidation of the metal in the hot moist environment.

The dryer unit as conceived should have counter-flow drying air; however, the blower as shown in the concept drawings is located at the feed inlet end.

Ducting would have to be run to the feed discharge end, consuming more of the limited space. Further layout and/or rearrangement will be required. The dryer would require rotary feed valves on both the feed inlet and perhaps the outlet to prevent escape of the drying gases.

The EES dryer has a scaled width of 1.2 m (4 ft), leaving insufficient space to park the front end loader, or fork lift truck if used instead, beside the dryer and still stay within the 2.4 m (8 ft) maximum legal width for highway vehicles. One or the other of the pieces of equipment will have to be narrowed. The off-gas burner (Item 14) is considerably larger than that depicted and will force a rearrangement of equipment on Trailer I. If a special permit 3.0 m (10 ft) wide trailer is acceptable, then there will be no problem provided the dryer is less than 1.5 m (5 ft) wide.

If the trailer width is limited to 2.4 m (8 ft), and this is desirable for use on rural roads, then a third trailer will be required even if testing verifies the basic concept. The conservative assumption is therefore made that the three trailer system will be required. The burner and dryer would be on one trailer and the other trailers would be rearranged to transport the balance of the process equipment.

Calculations by Parsons indicate a minimum of 15 kW (20 hp) is required for the screw drive rather than the 746 W (1 hp) shown on the EES concept drawings. Proposals from dryer manufacturers show total power requirements, including fans, up to 186 kW (250 hp), which is considerably greater than the 31 kW (41 hp) provided in the EES concept schedule of loads.

The price range for commercial equipment has been established at $27,000 to $180,000. Full scale testing of a final dryer system must be accomplished to verify performance and feasibility before the trailer conceptual design can be finalized into a production model. This could be conducted by either manufacturers or in a final design program.

Item 7 - Feed Conveyor

This conveyor should be enclosed to prevent wind scattering the dried waste and should have lifting lugs to permit the fork lift truck to position it. The belt should have cleats on it to prevent material slippage on the steep incline.

Item 8 - Converter

The pyrolytic converter is recommended to be cylindrical in cross section to assure uniform stirring and reaction in both the combustion and decomposition zones. A sketch of the 2.4 m (8 ft) diameter unit is shown as Figure 19. It should be constructed of Type 304L stainless steel. Until moderate duration tests of the char-in-shelves concept of insulation proves this system would indeed work, a design based on the use of a light weight, abrasion resistant, insulating brick lining must be recommended by Parsons. External insulation for personnel protection should be contained in an aluminum, weather-proof jacket.

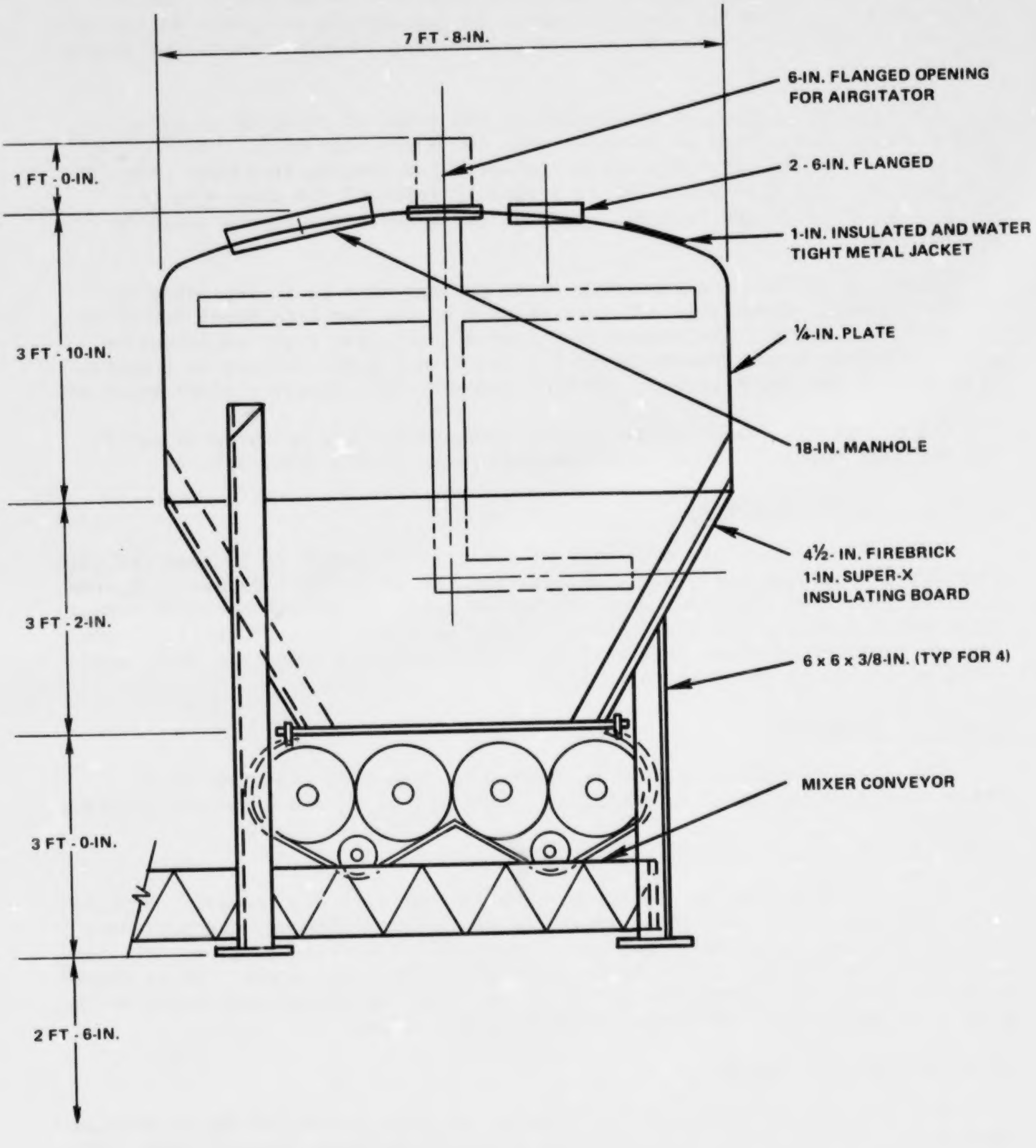

7 FT - 8-IN.
6-IN. FLANGED OPENING FOR AIRGITATOR
1 FT - 0-IN.
2 - 6-IN. FLANGED
1-IN. INSULATED AND WATER TIGHT METAL JACKET
3 FT - 10-IN.
¼-IN. PLATE
18-IN. MANHOLE
4½- IN. FIREBRICK
1-IN. SUPER-X INSULATING BOARD
3 FT - 2-IN.
6 x 6 x 3/8-IN. (TYP FOR 4)
MIXER CONVEYOR
3 FT - 0-IN.
2 FT - 6-IN.

Figure 19. Converter section.

Stirring and air injection can be accomplished with the "AIRGITATOR" concept; it should be fabricated of stainless steel and water-cooled. Height restrictions require that the drive motor be demountable or else attached to the side of the converter and rotation transmitted through a series of geared shafts.

Char product output is controlled by the speed of rotation of water-cooled tined drums dropping material onto two screw conveyors. The ducting about the drums and conveyors might require water cooling to reduce char temperature and should be air-tight to assure ignition of the char does not occur. An inclined conveyor will be required to move the cooled solid to the oil blender.

Start-up of the cold converter could perhaps best be accomplished by bracket-mounted retractable LPG burners such as the Sur-lite Model 2-H118-Ut-30, priced at $1200. The burners would be of stainless steel construction with the burner heads housed inside 7.6 cm (3 in.) pipes serving as a protection against the bed material. Several burners would assure uniform start-up.

If a portable (wand) burner proves adequate and can be operated safely, the Sur-lite Model PHIT-CH2 is recommended; its current cost is $175.

Item 9 - Cyclone (Off-Gas)

Standard cyclones are typically of too great a height to be used for this function of removing particulate matter from the converter off-gases. Custom units of Type 304L stainless steel should be used. A gravity operated tipping valve and a dust storage bin would be installed under the cyclone(s). Depending on practical problems that will be studied with the prototype unit, cost could be in the range of $5000 to $8000.

Item 10 - Condenser

The oil condenser should be fabricated of Type 304L stainless steel. Tests should be conducted to establish possible fouling and corrosion problems.

Items 11, 12, 13, 15, 19 and 31 - Fans and Blowers

No particular problems exist with the various fans and blowers. Detailed sizes and power will have to be specified after final flow and pressure drop designs can be established. Because of potential corrosion problems, all fans contacting the off-gas should be constructed of stainless steel. It is recommended that the two dryer fans (item 15) be placed in the exhaust ducts so that they will handle the cooled air having a lesser volume.

Item 14 - Off-Gas Burner

The Coen Burner Manufacturing Company, an organization having an excellent reputation for supplying combustion equipment of the type required here, indicates that an envelope size of 4.3 x 1.8 x 2.4 m (14 x 6 x 8 ft) would be required to supply the 11.6 GJ/h (11 x 10^6 Btu/hr) needed. The 1371°C (2500°F) gases would be diluted with air to achieve the desired 371°C (700°F) dryer inlet gas. Their estimated price for the burner, piping train, burner safety and control system, fans and refractory-lined chamber is $50,000.

Item 16 - Burner Exhaust

This would consist of a vertical steel stack to carry off any surplus hot gases and to also act as a flare stack. Its top would be 4.1 m (13 ft, 6 in.) above ground level. Drying air controls would regulate a by-pass damper to divert excess gases to the stack.

Item 17 - Dryer Exhaust Duct

Ducting must be incorporated between the burner (14) and the dryer (6), the dryer and fans (15), and between the fans and the cyclone (18). All ducting would have insulation with a weather-proof metal jacket to retain heat and provide personnel protection.

Item 18 - Cyclone (For Dryer)

The standard cyclone will have to be modified to have an eccentric hopper with its discharge located to one side of the trailer. The hopper discharge will have a rotating feeder or gravity dump valve. No other problems have been encountered or are expected.

Item 20 - Generator

The capacity of the generator will have to be increased from the 150 kW indicated by EES to 200 kW. This increase is caused by larger motor loads for process equipment, lighting on trailers, and movable flood lights for night operations. It also assumes that the Georgia Tech dryer will not be used and that a commercial rotary one be substituted.

Item 21 - Engine

The specified Waukesh engine is no longer available; the replacement unit would be Model H2475GU. Some engine manufacturers indicate they might have difficulty operating on such low heating value off-gas, and that the composition of the gas is critical to reliable performance. Installation of a LPG storage tank is recommended which would have a capacity to supply engine and converter under start-up period and when off-gas is too weak, or not produced for any reason. Switchover to LPG would be automatic, otherwise the operation would shut down. The engine and generator should be protected from weather in a sheet metal hood or enclosure.

The present design will be based on a Kohler generator set, for data and price. The Kohler price is also lower than Waukesha for one unit and quantity discount is a minimum of 25%.

It is recommended that the engine chosen be considered one of the components for the final development program; it might be operated at higher temperatures than normally used to reduce or, hopefully, eliminate corrosive problems from the off-gas. An experimental program for an engine for the EES concept has been conducted by the Georgia Institute of Technology for EPA. No report has been issued as of May 1977, but it is understood that a 6-cylinder spark-ignition truck engine (7.5 compression ratio) performed well with a dry simulated off-gas. The brake power output was approximately 0.6 of that when the engine was fueled with gasoline. Tests with actual pyrolysis gas are essential to developing final operating costs for the system.

Item 22 - Radiator, Converter Cooling Water

The radiator and cooling system would be sized to cool the AIRGITATOR, converter outlet feed drums, lower hopper bottom, and the water jacketing on the screw conveyors used for reducing the char temperature to prevent reignition and possible explosive condition developing when oil is added. The radiator would be a standard commercially available unit with a motor driven fan.

Item 23 - Compressor

The air compressor and air receiver would be a commercially available unit commonly used in service stations. The compressed air would be used for instrument control air and powering actuators for controlling the process such as dampers or valves.

Item 24 - Conveyor, Mixer to Storage Bin

This unit would necessarily be enclosed to prevent wind blowing away the char. Another conveyor or some means will be required to uniformly distribute the char-oil into the char-oil storage bin trailer (26).

Item 25 - Mixer

There is still some question as to how best to mix the oil and char product. A Littleford Model KM 300D mixer/grinder, 8.5 m^3/h (300 ft^3/h) capacity, would be one alternative; this unit costs approximately $20,000. A size 2424 Sprout-Waldron single-hammer attrition mill ($8,000) might also be considered. With oil currently commanding a much higher sales price per unit heating value then solid fuels, consideration should be given to eliminating this mixing operation in most cases.

Item 26 - Product Storage Trailer

In that this item is considered a part of the marketing activity rather than waste processing, it has not been discussed here, but rather is costed within the total system operating economics section.

Item 27 - Process Instrumentation and Controls

The EES concept has not progressed to a level where the developers have had to describe any instrumentation and controls as a part of the transportable pyrolysis system, but in production units they would be a very necessary and integral part of it.

The plant is intended to pyrolyze agricultural wastes from saw mills, cotton gins, sugar mills, and peanut processing plants, all having varying degrees of moisture depending on recent weather conditions. Manual (non-automatic) operation under these conditions, especially with a minimal work crew, would be unsatisfactory and potentially hazardous. Essential process variables must be automatically held to practical working tolerances within their operating ranges in order to assure total system operation with high energy recovery.

Control and instrumentation are required to provide proper control over the process, protect the plant from abnormal operating conditions that could be damaging, and continuously monitor operations against hazardous conditions developing, such as fire and explosion, for safety protection of personnel.

Parsons has attempted to identify the instruments and controls so that their cost is reflected in the estimate. Subsequent operations and tests of the final selected equipment configured for mounting on the trailers will be needed to verify and check out the instrumentation and controls, and the possibility exists that the need for some of this equipment could prove to be unnecessary.

The following control systems are recommended and their cost is included in the cost estimate:

A dependable burner management system is required to prevent a hazardous explosive condition. The burner flame must be monitored carefully at the time of change-over of fuel from LPG to off-gas and switched over when the off-gas Btu content is high enough to support combustion. The switching action reverses when off-gas Btu content is too low or in insufficient quantity.

Hot gas at the burner outlet would be monitored and a valve on the bypass to atmosphere will exhaust excessive gas when the temperature exceeds 370°C (700°F).

Temperature in and out of the dryer will be monitored and alarmed when normal operating temperature is not maintained.

Differential pressure across the dryer will control the vent to atmosphere to maintain a constant dryer pressure.

Current to the hammer mill will be monitored and controls will adjust the material feed rate so the current draw does not exceed 80% of full load current. The hammer mill will have a current read out on the control panel.

Differential pressure will be maintained and read out across the converter and cyclone and will be alarmed on a preset high differential.

Temperature within the converter will be read out at three levels. Temperatures of the hot gas out and the char discharged will also be measured. A level sensor system will monitor and control feed level.

The temperature of radiator water in and out will be measured and will be alarmed when a preset high temperature is reached. Thermostatic control valves will regulate cooling water to the Airgitator, water cooled drums in the converter, and the mixer conveyor.

The condenser temperature will be monitored in and out and will be alarmed when the temperature is not in proper operating range.

The following instrumentation has been identified as the minimum required for satisfactory operation of the pyrolysis plant:

- Control Room
  - Instrument Read-out and Equipment Control Switch Panel
  - Control Switches for 24 Equipment Drive Motors
  - Control Switch for Lighting

- Hammer Mill
  - Current (amperage) flow controls, feeder to hammer mill
  - Current flow sensor (R)*

- Dryer
  - Temperature - Inlet Hot Air (R)
  - Temperature - Effluent Air (R)
  - Air Flow - Drying Air (R)
  - Pressure Drop of Drying Air (L)*

- Converter
  - Height sensor for material to control flow of dried material into converter on a go no-go basis (L)
  - Thermocouples at 3 height levels (R)
  - Combustion air flow rate to Airgitator (R)
  - Loss of air flow alarm (R)

- Burner
  - Off-Gas to LPG automatic monitor & switch-over
  - Ignition controls
  - Flame failure safety controls
  - Excess heat hot gas by-pass to atmosphere

- Dryer Exhaust Cyclone
  - Exhaust gas pressure drop (L)

- Converter Off-Gas Cyclone
  - Off-gas pressure drop (L)

- Off-Gas Condenser
  - Temperature, off-gas from converter (R)
  - Temperature, leaving condenser (R)
  - Off-gas pressure drop through condenser (L)

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* (R) and (L) refer to remote readout and local indicator respectively.

Cooling Water System
- Temperature, cooling water supply (R)
- Temperature, water leaving tines (Drums) (L)
- Temperature, water Leaving Airgitator (L)
- Temperature, water leaving char cooling conveyor (L)

Engine-Generator
- Amperage (R & L)
- Voltage (R & L)
- RPM or Hertz (R & L)
- Transfer switch or controls from LPG to Off-Gas (R & L)
- Off-Gas supply pressure (R & L)
- Engine oil pressure (L)
- Engine oil failure (R)

Detailed estimated costs, presented in summary form later are shown in Table 17.

TABLE 17. CONTROL & INSTRUMENTATION COST ESTIMATE

Panel, 2 m (6 ft) (Console)	$7,000
Burner Management System	*
Off-Gas Analyzer & Switch Over System	$10,000
Dryer Air Temperature Loop-Bypass to Atmosphere	$7,500
Temperature Loop Across Dryer (3 Points)	$3,300
Differential Pressure Across Dryer	$1,600
Hammer Mill Current Monitor & Feed Control System	$600
Differential Pressure Across Converter	$1,600
Temperature Within Converter (3 Points)	$3,300
Temperature Within Condenser (3 Points)	$3,300
Material Feed Level in Converter (3 Points)	$3,800
Cooling Water Radiator Temperature In & Out	$2,200
Control Panel for Engine	*
Instrumentation	$44,200
Installation Labor	$30,000
TOTAL COST INSTALLED	$74,200

* Cost included with major equipment.

Item 28 - Agitator

A preliminary design of an agitator (AIRGITATOR) has been made to be in accordance with the Georgia Tech requirements. The unit would be constructed of Type 304L stainless steel and be water cooled using water from the cooling water system and air cooled radiator (22).

Item 29 - Front End Loader Storage

See Item 1.

Item 30 - Cat Walks

The extent of cat walks, ladders, and stairs required for access to the plant during operation have been estimated along with their cost. Complete peripheral coverage as suggested by the developer does not appear warranted. The cat walks would be light weight aluminum framing and aluminum grating. The cat walks can be designed to latch in the raised position and fold down for the operating position. Removable posts and chains would protect personnel from falling.

Items 32 and 33 - Trailers I and II

Price and dimensional data have been received from Fruehauf. The 40-ton Model C40D-J2 trailer would be required in lieu of the suggested Model C25D-J2 because of plant weight. Fruehauf has advised that the trailer could be extended 6 feet, from 16 feet to 22 feet, in its mid-section, should additional length be required. During final design of the plant, the loading and placement of equipment will have to be carefully considered for weight, balance, and dynamic stability during transit.

Item 34 - Conveyor, Converter to Mixer

The process developers did not identify a conveyor from the converter discharge to the mixer (25). One is required to horizontally move the char and then elevate it to the top of the mixer. The exact configuration and equipment required downstream of the converter is still not defined and the exact type of char/oil mixer (25) to be used has not been determined.

Item 35 - LPG System

As discussed under items (6) and (21), a LPG system will be required for start-up and during times when the off-gas is insufficient to support operational demands. The system would have a capacity of 1100 dm^3 (300 gallons), sufficient for approximately 8 hours of operation. The system would be refilled after each second start-up. The engine and burner would have to be equipped with a dual set of burners or an LPG/air dilution-mixer to lower the heating value of the LPG (88.61 MJ/m^3 or 2250 Btu/ft^3) to that of the off-gas (5.91 MJ/m^3 or 150 Btu/ft^3).

Item 36 - Rotary Feeder

The Dryer (6), the inlet to the Converter (8), and the cyclone discharges will require air locks to prevent flow of air or off-gas. Rotary feed valves driven by gear head motors through a roller chain drive would be used.

Power Requirements

The transportable pyrolysis system as conceived must be completely independent of outside utilities, except for periodic replenishment of LPG fuel used for start-up. As such, the system must be self-supporting in operation and supply its own power needs. Parsons has investigated the individual power requirements of the various pieces of equipment in order to verify the size of the off-gas engine and the generator that it drives. It is concluded that the electrical load will be approximately 40 percent greater than that indicated by EES (120 kW) or 168.5 kW.

Table 18 shows a schedule of process equipment power requirement. The tabulated data are as close as can be identified at this preliminary stage and would be subject to modification in the final design phase of development.

TABLE 18. SCHEDULE OF PROCESS EQUIPMENT POWER REQUIREMENTS

Item No.	Equipment Description	Power Required kW	Power Required hp
2	Bin Conveyor (Deleted)	-0-	-0-
4	Hammer Mill Feeder	1.5	2.0
5	Hammer Mill	56.0	75.0
6	Dryer Drive	7.6	10.0 (1)
6A, 6B	Dryer Rotary Valve Drives, 2 @ 0.5 hp	0.7	1.0
7	Conveyor - Dryer to Converter	3.7	5.0
8	Converter - Input Rotary Valve Drive	0.4	0.5
28	Airgitator Drive	2.2	3.0
8A	Converter - Tine drive	3.7	5.0
11	Condenser Fan	1.1	1.5
12	Off-Gas Fan - O.G. to Burner	4.1	5.5
13	Combustion Air Fan to Burner	11.2	15.0 (2)
15	Dry Air from Dryer Fans, 2 @ 30 hp	44.8	60.0
19	Process Air Blower - Roots Type	3.7	5.0
22	Cooling Water Radiator Fan	3.7	5.0
22A	Cooling Water Circulating Pump	1.5	2.0
23	Instrument Air Compressor	3.7	5.0
24A	Conveyor - Converter to Grinder-Mixer	2.2	3.0
24	Conveyor - Char/Oil from G-M to Storage	3.7	5.0
25	Char/Oil Mixer	2.2	3.0
25A	Oil Spray Feed Pump	0.7	1.0
31	Engine Blower - Off Gases to Engine	1.5	2.0
	Process Equipment Power Sub Total	160.0	214.5
	Plant Lighting	2.5	
	Work Area Portable Lighting	4.0	
	Instrumentation and Controls	2.0	
	Total Power	168.5	
	Use Rated Power	200.0	

Notes: (1) Not well identified; commercially available dryers range from 40 to 250 hp total.
(2) Not determined; depends on burner combustion chamber pressure.

The increased power load results principally from the dryer and its fans (Items 6, 6A, 6B, 15), combustion air fan (Item 13), plant and work area lighting, and instrumentation and controls. No statistical diversity factor can be established at this time, and to avoid overloading the engine-generator at plant start-up, the various pieces of equipment should be started sequentially.

The generator capacity should be oversized by approximately 20% to 200kW to give a reasonable safety margin. Increasing the generator rated capacity will also increase the horsepower of the off-gas engine, its size, and use of off-gas. A portion of the final developmental study should be devoted to optimizing relative energy distribution of the three product streams so that net energy is maximized. This would be accomplished by variations in the feed/air ratio.

SYSTEM ECONOMICS

Equipment Cost Estimate

Standard industrial estimating sheets were prepared by engineering construction specialists at Parsons to establish the probable costs of the mobile pyrolysis system. A summary of the principal elements of cost is presented below, for both the first prototype unit and for production of a lot of 100.

Several important assumptions were made in deriving the cost estimate. Most of these assumptions lead towards an estimate that could be at least $100,000 low if additional developmental work demonstrates them to be false. Experience demonstrates that estimates prepared prior to completion of final R & D can be considerably below ultimate costs because of extra features found necessary and generally increased complexity of the total system. None of the developmental costs are included within the cost estimate, i.e., a strictly industrial organization would have to attribute higher costs to each unit to recover these past expenditures.

The assumptions are as follows:

- A commercial rotary dryer will be required to meet performance requirements and a third trailer is required.
- The basic pyrolytic converter as now developed will meet performance requirements. Stainless steel construction has been priced.
- The internal combustion engine will function reliably with the corrosive low-Btu gas.
- The burner can be packaged to fit the trailer and operate properly with the off-gas.
- A simple hopper-screw conveyor mixer for the char-oil blending will suffice.
- An 8-hour LPG storage system is sufficiently large.

- The cost of a fuel storage bin (Item 26) and bin conveyor (Item 2) are not included.
- The controls and instrumentation specified are adequate.
- A 10% procurement cost has been added to all vendor quotations.
- A 15% contingency of total direct costs has been employed to cover items where design uncertainty exists or where items might have been inadvertently omitted.
- No escalation has been used over early 1976 prices.
- No sales tax is included.

The cost estimate summary is as follows:

Item	Original (Prototype)	Production (100 or more)
Major Equipment		
Loader	$18,100	
Receiving Bin	3,100	
Conveyors (4)	9,100	
Hammer Mill	15,600	
Dryer, with Fans	115,000	
Converter and Accessories	72,500	
Cyclones (2)	15,000	
Condenser	8,000	
Gas Burner	57,400	
Process Air Blower	3,500	
Engine-Generator	41,000	
Water Radiator, with Accessories	6,300	
Char-Oil Mixer	3,400	
Control Room	2,500	
Engine Blower	2,000	
Electrical System	19,000	
Instrumentation and Controls	74,200	
Trailers (3) Including Catwalks	46,000	
LPG System and Controls	5,000	
Painting	3,000	
Other Equipment	14,200	
Material Sub-Total	533,900	453,815 *
Labor Sub-Total	51,000	38,000
Sub-Total	584,900	491,815

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* The various mix of quantity discounts, on a weighted basis, averages approximately 15% and hence a multiplier of 0.85 was used for the material sub-total.

Item	Original (Prototype)	Production (100 or more)
Direct Material	$30,000	$24,000
Labor	20,000	14,000
Direct Cost Total	634,900	529,815
Engineering	40,000	1,000
Total Direct Cost	674,900	530,815
Contingency @ 15%	100,000	80,000
Freight Allowance	4,000	4,000
Grand Total	$778,900	$614,815

Operating and System Costs

As with any other waste-to-energy processing system, the analysis of the total system economics for the mobile agricultural waste pyrolyzer can be performed with meaningful accuracy only by using actual information obtained for a specific region. Surveys must be conducted to establish waste quantities, points of origin, and their seasonality. Letters of intent must be obtained for the supplying of wastes and the purchase of the fuel product, along with the various local cost factors. Key assumptions can be made in advance, however, that will permit conclusions to be drawn as to the basic economic feasibility of the system and that will indicate the sensitivity of profit to various cost elements. Such an analysis, under several sets of assumptions, is presented here.

A single value, $800,000, for the investment in the mobile system has been used. While slightly higher than even the single unit cost derived above, use of this cost is within the range of accuracy of the estimate and will allow for a moderate degree of cost escalation. Based on a 10-year useful life and 8 1/2% interest, the annualized equipment cost is therefore $121,936.

Other costs have been developed under tne specific assumptions listed in Cases I through IV below. Two fundamental exceptions have been taken with the preliminary economic analysis made by EES. The nature of the pyrolysis equipment precludes operation on other than a continuous basis and only a 3-shift day, 7 day per week case has been considered; the unit must be always manned by at least two personnel while operating. Where EES based their analysis on waste being delivered at no cost to the processing facility or at a disposal charge of $3/ton, the Parsons calculations assume that both the no cost and the drop charge cases might be optimistic assumptions and that a payment to the waste generator of $5/ton should be considered as the conservative approach. Such purchase of wastes has become common in the wood products industry in recent years.

The first two cases analyzed have an operating cycle of 14 days of waste conversion and then 2 days to move to the next site and set up again; any minor maintenance would be performed during the set-up time, with major maintenance being conducted during longer out-of-operation periods during the year. A stockpile of 2540 Mg (2800 tons) of 50% moisture waste is therefore required for operation of the 200 TPD system. At each site approximately 571 Mg (630 tons) of product would be produced, having a total energy content of 15.29 TJ (14.49×10^9 Btu).

These two case assumptions are as follows:

Factor	CASE I (Optimistic)	CASE II (Conservative)
Production days per year	294	238
Product per year, Mg (ton)	12 000 (13,230)	9 716 (10,710)
Sites per year	21	17
Total working days per year	336	272
Cost of waste, \$/Mg (\$/ton)	0	5.50 (5)
Selling price of product, \$/Mg (\$/ton)	38.58 (35)*	30.86 (28)*
Annual labor cost, \$	191,280	155,560
Annual maintenance cost, \$	20,000	40,000
Annual transportation cost, \$	33,440	27,680
Annual supply cost, \$	4,000	6,000

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* \$35/ton corresponds to \$1.52/10^6 Btu and \$28/ton to \$1.22.

The costs above were derived as follows:

Labor - 2 persons continuously working (24 hrs/day) during the listed working days per year at a burdened rate of \$10/hour. In case I, a supervisory cost of \$30,000 was added and for Case II \$25,000.

Maintenance - 4% of capital cost for Case II and one-half of that for the optimistic case.

Transportation - Tractor with driver rental at \$30 per hour for 3 hours of each working day. To this has been added the annualized cost of two product storage trailers at \$8000 each with a 5 year useful life.

Supplies - Estimates for LPG and miscellaneous small parts.

Table 19 shows the summary of annual costs and revenues for the Cases I and II. It can be seen that for the optimistic case a profit of more than \$90,000 per year could be realized, while a loss of some \$290,000 could result

TABLE 19. ECONOMIC ANALYSIS SUMMARY

	Case I	Case II
COSTS		
Capital Amortization	$121,936	$121,936
Waste	0	238,000
Labor	191,280	155,560
Maintenance	20,000	40,000
Transportation	33,440	27,680
Supplies	4,000	6,000
	370,656	589,176
INCOME		
21 x 630 x 35	$463,050	
17 x 630 x 28		$299,880
PROFIT (LOSS)	92,394	(289,296)
PROFIT (LOSS)/Ton raw waste	$1.57	($6.08)
PROFIT (LOSS)/Mg raw waste	$1.73	($6.70)

if all of the several conservative assumptions of Case II indeed were to be true. The numbers demonstrate the need to operate the equipment for the maximum possible number of days per year on a continuous basis and the high sensitivity to product sales price and value imputed to the waste.

With Cases I and II establishing the importance of principal key variables in permitting system profitability, several variations in Case I assumptions have been made to determine cost sensitivities. In the first (Case III), all assumptions were held constant other than the selling price of the fuel. The upper price of $76.68/ton below was established by assuming that fuel oil could soon be selling for $0.50/gallon ($3.33/10^6 Btu) and that the waste-derived fuel could approach that value as a limit. As yet unreported tests at the Pittsburgh Energy Research Center demonstrate slurries of the solid fuel in oil can be successfully fired and hence the assumption would appear to be a reasonable one. Case III net costs are as follows:

Selling Price of Product		Unit Net Profit (Loss)	
$/Mg	$/Ton	$/Mg Waste	$/Ton Waste
30.86	28.00	(0.004)	(0.004)
38.58	35.00	1.73	1.57
60.63	55.00	6.69	6.07
84.52	76.68	12.07	10.95

An annual net profit of $643,820 would be realized at the highest assumed selling price, a most favorable situation considering the capital investment is approximately the same if 100 units were to be built. It should also be noted in the calculations above that a selling price of $28/ton results in essentially a break-even situation.

In the Case I assumptions, the equipment was producing fuel 80% of the entire year, and taking into account moves and set-up times had a total utilization factor of 0.92. Agricultural wastes have a high degree of seasonality and this effect on profitability was examined (Case IV) by calculation of two reduced utilization factors. During down times it was assumed that no labor costs would be incurred and that the equipment could be stored for $400 per month. Case IVA is identical to Case I and the two variations are as follows:

Factor	Case IVB	Case IVC
Production days per year	266	210
Product per year, Mg (ton)	10 859 (11,970)	8573 (9,450)
Sites per year	19	15
Total working days per year	304	240
Cost of waste, $/Mg ($/ton)	0	0
Selling price of product, $/Mg ($/ton)	38.58 (35)	38.58 (35)
Annual labor cost, $	172,920	136,200
Annual maintenance cost, $	18,000	16,000
Annual transportation cost, $	30,560	24,800
Annual supply cost, $	4,000	4,000
Storage	800	1,600
Total Costs (Incl. Amort.)	$348,216	$304,536
Income	418,950	330,750
Profit	70,734	26,214
Profit/ton raw refuse	$1.33	$0.62
Profit/Mg raw refuse	$1.47	$0.69

It can thus be seen that under the basic assumptions of Case I, the system proves profitable down to a production utilization factor of 0.57 or a total annual factor of 0.66.

ENVIRONMENTAL CONSIDERATIONS

Little specific experimental work has been conducted on effluent compositions or other environmental considerations of the operation of 200 TPD mobile pyrolysis systems. Many hundreds of hours of pyrolysis and off-gas combustion have been accumulated on the several units thus far constructed with no visible emissions being noticed under steady state conditions. In an analysis of the stack while wood wastes were being used as the feed, Georgia Tech found the following:

Component	Concentration
Oxygen	0.9%
Nitrogen	69%
Carbon Dioxide	7.7%
Carbon Monoxide	30 ppm
Particulates	0.0005 g/Nm^3 (0.0002 grains/SCF)
Hydrogen Sulfide	0.009 ppm*
Nitrogen Dioxide	0.04 ppm*
Ammonia	0.09 ppm*
Sulfur Dioxide	0.4 ppm*

Such results are to be expected from the combustion of a clean pyrolysis gas. NO_x could be significantly higher if high temperature combustion occurred.

Gaseous and particulate matter could be emitted from the waste introduction and char discharge systems of the pyrolysis converter unless proper valving and pressure differentials are designed into the equipment.

Emissions from the drying system need to be examined for the final dryer-mechanical separator equipment chosen. Wastes containing large quantities of fines could require a fabric filter (bag house) emission control unit and odor levels should be examined in the final configuration. Careful control of excessive temperatures within the dryer should eliminate this potential problem other than with unusual wastes that might contain a high degree of volatile matter.

Through operation of the off-gas condensing system above the dew point temperature of water, no liquid wastes will be formed at the facility. The converter should not be permitted to be washed down onto open ground and the finished product(s) should be protected against leakage by any route into ground water supplies.

Noise power levels below OSHA regulations can be readily obtained through proper design.

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* None detected; value listed as limit of detection.

SECTION 7

ANDCO-TORRAX PYROLYSIS SYSTEM

INTRODUCTION AND SUMMARY

The Andco-Torrax system converts municipal refuse into a usable gas by pyrolysis and then combusts the gas to produce heat for generation of steam. Noncombustible materials are slagged at temperatures up to 1650°C (3,000°F). The principal unit is a vertical reactor system that involves an air-blown partial oxidation pyrolysis process. Refuse from a storage pit, untreated and unsorted except for large bulky materials, is introduced via a feeder charged by a crane bucket. The refuse slowly descends through the reactor, encountering hot gases that dry it, and then thermally convert it to gases, char, and ash. The char is burned at the bottom of the reactor with air preheated to a sufficient temperature to slag the ash and metals. Figure 20 shows a schematic of the reactor or gasifier as now being built for commercial application.

A demonstration plant using this principle was designed and constructed by Andco Incorporated and the Carborundum Company; it was first operated in the second quarter of 1972. Funding was largely supplied by the Federal EPA, with additional support from New York State, Erie County, the American Gas Association, and the developer. Since the summer of 1972 this plant has operated or been available for use as an engineering development facility to evaluate various design features and to test the process on a number of industrial wastes admixed with municipal solid waste.

Design of the first commercial unit, now built in Luxembourg, utilized the information obtained from the demonstration plant, but incorporated several important changes. These include regenerative heat exchange for preheating the gasifier air and an electrostatic precipitator. Three additional steam generating systems are now being constructed in Europe. The Luxembourg plant is in start-up phase with a capacity of 200 Mg/d and will produce steam for use in a turbo-electric generator.

For The Ralph M. Parsons Co. to develop a basis for a range of larger sizes, Andco Incorporated provided design and cost information utilizing a 300 Mg/d (331 TPD) module. These designs were, in turn, based on the experience with the Luxembourg plant. Details for a 3 module 900 Mg/d (992 TPD) plant were developed with an extrapolation to two other sizes, a one module 300 Mg/d (331 TPD) plant and a five module 1500 Mg/d (1,653 TPD) plant.

The base case plant in this report has a capacity of 900 Mg/d (992 TPD) and it produces 2215 Mg/d (2,442 TPD) of steam at 3.4 MPa (493 psia) and

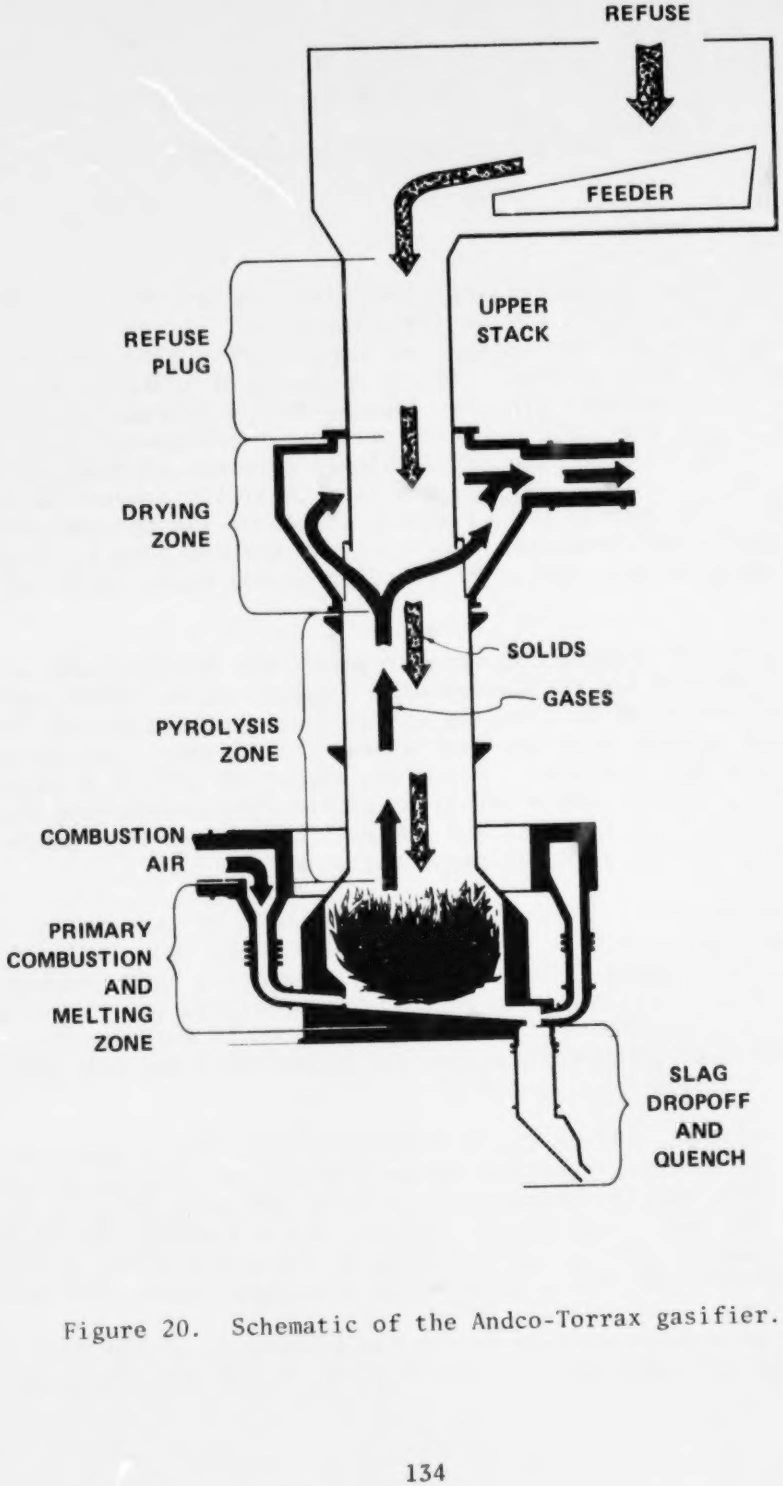

REFUSE
FEEDER
REFUSE PLUG
UPPER STACK
DRYING ZONE
SOLIDS
GASES
PYROLYSIS ZONE
COMBUSTION AIR
PRIMARY COMBUSTION AND MELTING ZONE
SLAG DROPOFF AND QUENCH

Figure 20. Schematic of the Andco-Torrax gasifier.

385°C (725°F). A conversion efficiency of 76% is estimated with a net thermal efficiency, taking into account electric power requirements, of 59%.

Residue as slag is produced at the rate of 212 Mg/d (234 TPD). Emissions in the stack gas are 88 ppm HCl, 125 ppm SO_x, 115 ppm NO_x, and 3 to 4 ppm of hydrocarbons as measured from the demonstration plant. Using an electrostatic precipitator, particulate matter can be expected to be significantly below the federal EPA standard of 0.08 gr/SCF at 12% CO_2.

Construction costs in 1976 dollars is estimated at $30.6 million and capital requirements at $34.94 million. The annual operating cost is $2.74 million. A net unit cost was determined by using an amortization rate of 8-1/2% over 20 years. Credit was taken for drop charges of 0, $5, and $10 per ton. The net cost of producing steam was then $8.83/Mg ($4.00/1000 lb) at zero drop-charge and $4.36/Mg ($1.97/1000 lb) at $10/ton drop-charge.

Costs as a function of plant size were estimated by extrapolating 900 Mg/d plant values to a one module (300 Mg/d) and to a five module (1500 Mg/d) plant. The capital costs are $14.99 million and $51.23 million respectively. The corresponding unit costs for the 300 Mg/d and 1500 Mg/d plants are, for a zero drop charge, $12.68/Mg ($5.75/1000 lb) and $7.58/Mg ($3.46/1000 lb) respectively. For a $10/T drop charge, the unit costs are $8.21/Mg ($3.72/1000 lb) and $3.11 ($1.42/1000 lb) respectively. These costs indicate that the system is competitive with oil-based steam generators and in some areas with coal based steam generators.

Course shredding of the raw refuse with recovery of materials should be considered if added equipment costs are more than balanced by revenues from material sales. Testing the Andco-Torrax reactor with a shredded feed would be needed.

CONCLUSIONS

- The Andco-Torrax system as a steam generator can now be considered as an available candidate for installation in a community. With several commercial-scale facilities now in construction or undergoing start-up testing, possible clients can review capital and operating cost data to learn how this approach compares economically with waterwall combustion systems. Total effluent gases to generate a unit of steam can be less than in the mass burning incineration case, and, if other cost factors do not cancel out this advantage, this pyrolysis approach could become a serious competitor to the older combustion technology.

- Clean up of the rather low heating value off-gas for pipeline transport to a utility cannot be recommended by Parsons based on existing data. The loss of sensible heat in such an application is another disadvantage to this approach once suggested by the early developers.

- In communities where no client exists for steam, and electric power costs are somewhat higher than average, the financial feasibility of adding a turbine-electric unit should be considered.

- The glassy slag residue produced is essentially organic free and can be used as clean fill or as a base for building materials.

- Pollutant emissions are low enough to meet local, State, and Federal environmental requirements in most areas of the U.S.

- Cost data presented in this report, although in 1976 dollars, should permit valid projected comparisons with fossil fuel generated steam, in that the market value of steam should escalate with the economy.

- High temperature systems can always benefit from improved materials of construction and R&D should be continued for such improved refractories and metals. Cycling of high temperature processes should be avoided and the Torrax equipment will enjoy lowest maintenance costs when operated on a steady basis.

- Capital costs increase almost linearly with plant size because of modularization of most of the plant components. Unit steam costs decrease somewhat linearly with increasing plant capacity, with a flattening of unit costs above about 1200 Mg/d.

LUXEMBOURG PLANT PROCESS DESCRIPTION

In Luxembourg, a 200 Mg/d plant has just been completed and is in the start-up phases. Figure 21 shows a schematic of the gasifier and secondary combustion chamber (SCC) while Figure 22 shows a schematic layout of the system. This includes the gasifier, SCC, two regenerative heat exchange towers filled with ceramic/checker-work brick, a waste heat boiler, and an electrostatic precipitator. Air for the reactor is compressed and passed through one of the regenerative towers while the other is being heated with a portion of the hot gases from the SCC. Particulate removal is affected by a slagging in the combustor and by passing all exhaust gas streams through the electrostatic precipitator.

The Torrax installation is part of a complex that includes two conventional grate incinerators to process a total of 600 Mg (661 tons) per day of municipal waste from the regional area of Luxembourg City. The boiler is a three-pass vertical combination radiation/convection boiler with the first of three passes being in the radiation portion. There is a superheater at the end of the radiation section and an economizer in the third pass. Performance of the boiler with a feed water temperature of 110°C (230°F) is designed to produce a maximum of 30 Mg/h (33 tons/hr) of steam at 3.4 MPa (493 psi) and 385°C (725°F). The boiler has been designed for a maximum gas throughput of 36 800 Nm^3/h (22,800 SCFM), a maximum gas temperature of 1370°C (2500°F), and a nominal gas temperature of 1250°C (2282°F). The steam produced from the Andco-Torrax unit and the incinerators is led to a 7 MW turbine-generator producing electricity at 10 kV. The turbine-generator is designed for the conversion of 600 Mg (661 tons) per day of refuse with a lower heating value of 8.4 MJ/kg (3,611 Btu/lb). A second turbine-generator will be installed as refuse production increases. Other details can be found in Reference 13.

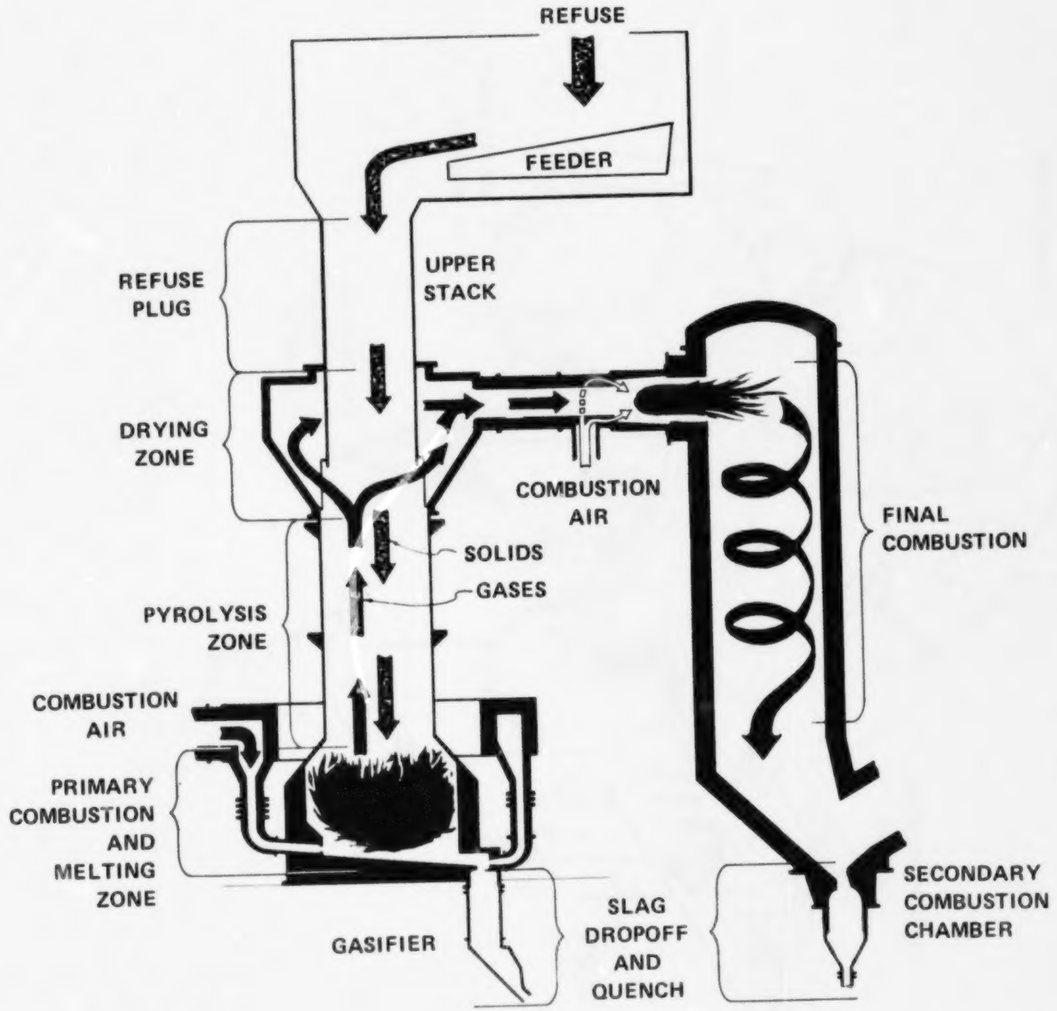

REFUSE
FEEDER
UPPER STACK
REFUSE PLUG
DRYING ZONE
COMBUSTION AIR
FINAL COMBUSTION
SOLIDS
GASES
PYROLYSIS ZONE
COMBUSTION AIR
PRIMARY COMBUSTION AND MELTING ZONE
GASIFIER
SLAG DROPOFF AND QUENCH
SECONDARY COMBUSTION CHAMBER

Figure 21. Arrangement of Andco-Torrax gasifier-combustion chamber at Luxembourg.

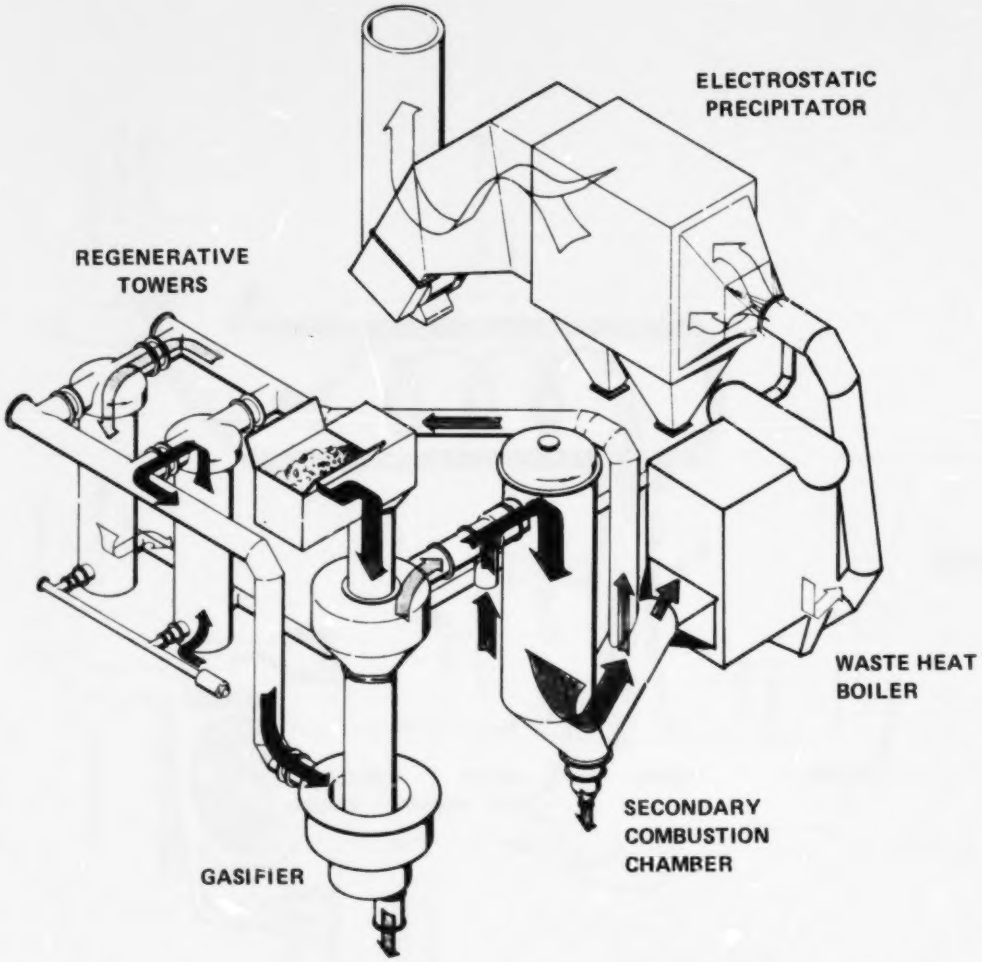

ELECTROSTATIC
PRECIPITATOR
REGENERATIVE
TOWERS
WASTE HEAT
BOILER
SECONDARY
COMBUSTION
CHAMBER
GASIFIER

Figure 22. Layout of Andco-Torrax system at Luxembourg.

THREE MODULE PLANT PROCESS DESCRIPTION

Three Andco-Torrax modules are used to process 900 Mg/d (992 TPD) of municipal refuse. Figure 23 shows a schematic flow diagram of a single module. The train of equipment shown is duplicated for each module except for the refuse pit, crane, and the slag collection pit. Refuse is introduced to the receiving pit and an overhead crane places material into the feed hopper for each gasifier. The refuse composition is that from the 1975 EPA Report to Congress (SW-16) and shown in the Purox Section. The analysis can be rearranged for use in computations made by Andco as dry combustibles 54.2%, dry non-combustibles 20.7%, and moisture 25.1% by weight. Slag from each of the gasifiers and each of the secondary combustion chambers is sent to a single slag pit from which the residue is conveyed automatically to trucks for removal. The process requires the following major pieces of equipment:

1. Receiving area and refuse pit
2. Crane - A single crane and clamshell or orange peel bucket can be used to pick up a load and deliver it to one of the three gasifier feed hoppers. Two grab buckets may be needed for redundancy where 3 or more gasifier modules are installed.
3. Feeder - Raw refuse from the crane is dropped into a hopper with a ram feeder mechanism near the top of the gasifier.
4. Gasifier
5. Slag Quench - Slag formed in the hearth area of the reactor runs into a slag tank filled with water for quenching.
6. Secondary Combustion Chamber (SCC) - To receive and burn the hot off-gases and entrained char from the gasifier to produce a high temperature exhaust gas. Additional slagging of fly ash occurs also, which is quenched.
7. Waste Heat Boiler - To convert the heat in the secondary combustion chamber exhaust gas to steam.
8. Regenerative Towers - Two checker brick-filled towers operate alternately for heating the combustion air to the gasifier, with heating of the bricks by a portion of the SCC exhaust gases.
9. Electrostatic Precipitator - For removing particulate matter from the exhaust gases from the regenerative towers and the waste heat boiler.
10. Air Moving Equipment - For introducing primary combustion air through the regenerative towers to the gasifier, secondary air to the SCC, and exhausting the cleaned exit gases to the flue gas stack.

Off-gases from the gasifier contain hydrogen, carbon monoxide, carbon dioxide, hydrocarbons, nitrogen, water vapor, and char plus ash particulates.

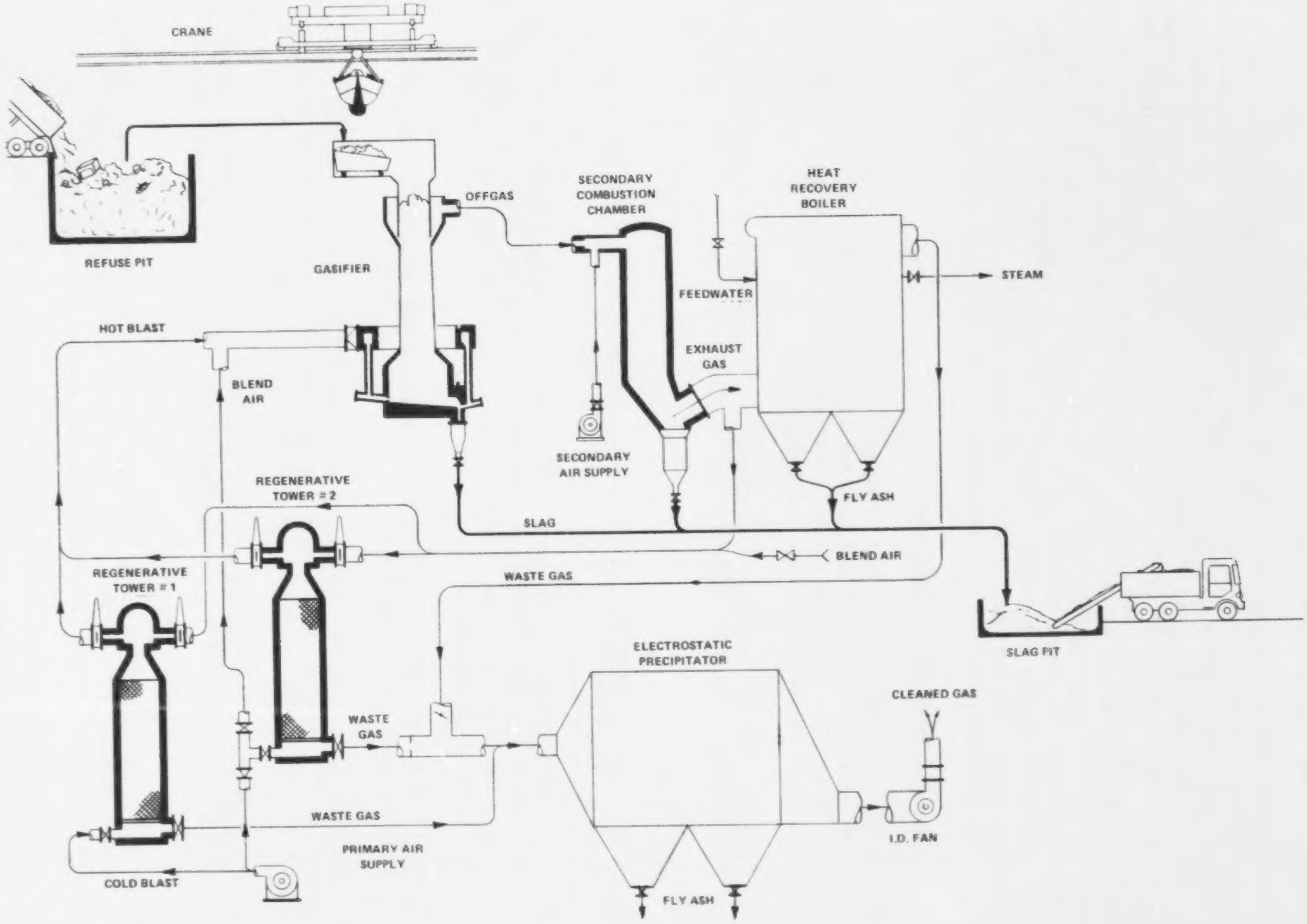

CRANE
REFUSE PIT
GASIFIER
OFFGAS
SECONDARY
COMBUSTION
CHAMBER
HEAT
RECOVERY
BOILER
STEAM
FEEDWATER
EXHAUST
GAS
SECONDARY
AIR SUPPLY
FLY ASH
HOT BLAST
BLEND
AIR
REGENERATIVE
TOWER # 2
SLAG
BLEND AIR
REGENERATIVE
TOWER # 1
WASTE GAS
SLAG PIT
ELECTROSTATIC
PRECIPITATOR
CLEANED GAS
WASTE
GAS
WASTE GAS
PRIMARY AIR
SUPPLY
I.D. FAN
COLD BLAST
FLY ASH

Figure 23. Schematic flow diagram of Andco-Torrax system.

With the high nitrogen content, the higher heating value of the gas is in the range of 3.94 to 4.72 MJ/Nm^3 (100 to 120 Btu/SCF). For one composition obtained from the demonstration plant test unit, as shown in Table 20, the higher heating value was 4.25 MJ/Nm^3 (108 Btu/SCF). When account is taken of the sensible heat (427°C or 800°F) and the heating value of the char particles, the total HHV becomes 6.89 MJ/Nm^3 (175 Btu/SCF). This gas is not useful for chemical synthesis and as a fuel must be burned in a closely coupled secondary combustion chamber to recover the high sensible heat.

TABLE 20. GAS COMPOSITION

Constituent	Vol %
CO	13.1
H_2	12.5
CH_4	2.0
C_2's	0.3
CO_2	10.1
N_2	43.5
H_2O	17.0
Total	98.5

HHV = 4.25 MJ/Nm^3 (108 Btu/SCF)

Char and sensible heat included in total heating value to secondary combustion chamber

HHV (Total) 6.89 MJ/Nm^3 (175 Btu/SCF)

HEAT AND MASS BALANCE

Figure 24 shows a mass balance for the various streams in the Andco-Torrax system, with the values given being based upon one Mg of raw refuse feed. Figure 25 shows an overall mass flow block diagram for a 900 Mg/d plant. In Figure 26 is shown a heat balance based on the energy input from one Mg of refuse, while Figure 27 shows an overall heat balance for a 900 Mg/d plant with electric power requirements. Table 21 shows the details for electric power requirements for a 300 Mg/d module. In assessing the thermal performance of the system to produce steam, efficiencies are used with some variation in definition. The heating value of the fuel is used in the denominator. If there is much moisture, the difference in lower and higher heating value is quite significant. To make steam, use of the lower heating value is more realistic and used in Europe, but the higher heating value is used generally in the U.S. to calculate thermal efficiencies. Values for

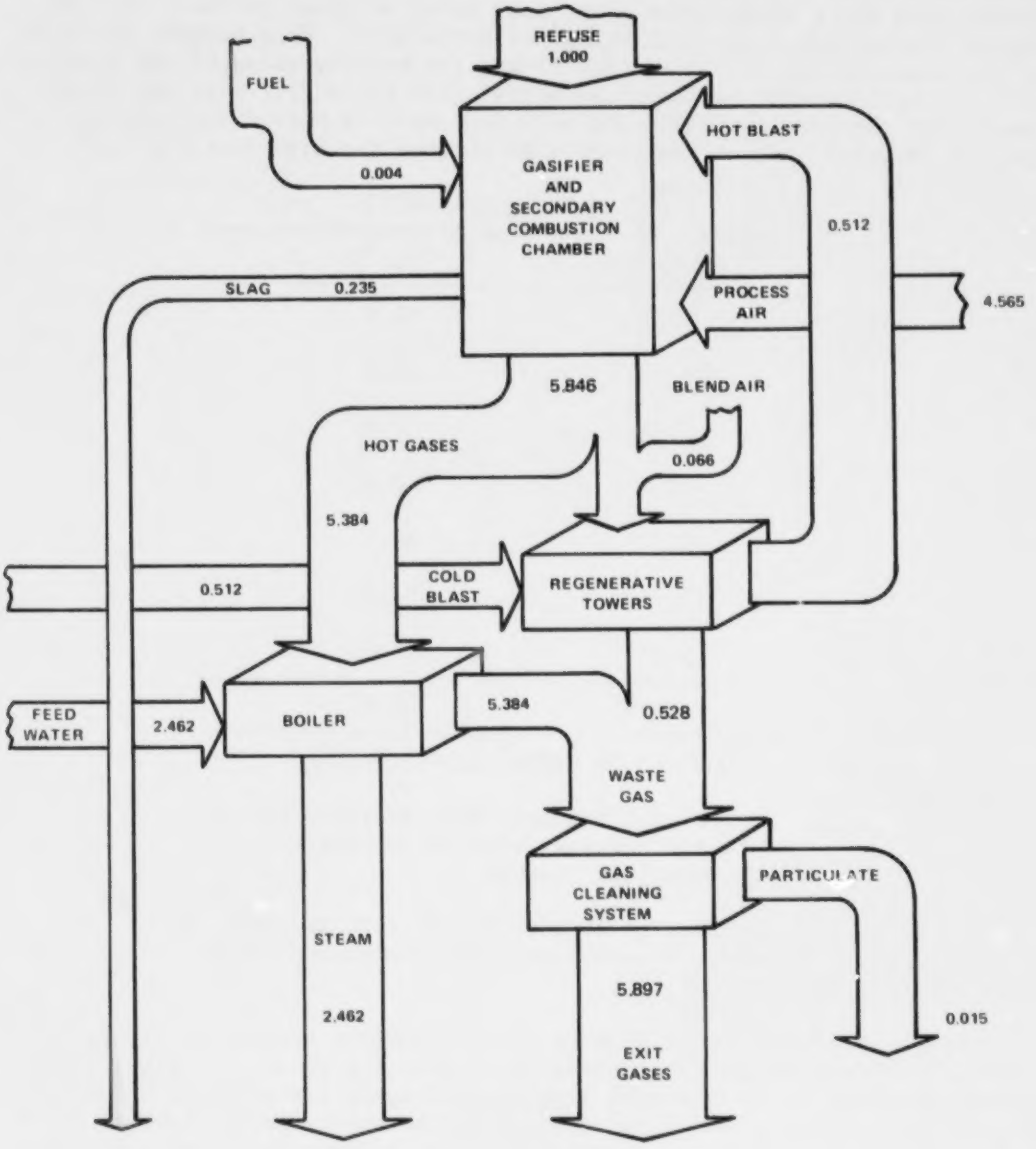

REFUSE
1.000
FUEL
0.004
GASIFIER
AND
SECONDARY
COMBUSTION
CHAMBER
HOT BLAST
0.512
SLAG
0.235
PROCESS
AIR
4.565
5.846
BLEND AIR
HOT GASES
0.066
5.384
COLD
BLAST
0.512
REGENERATIVE
TOWERS
FEED
WATER
2.462
BOILER
5.384
0.528
WASTE
GAS
GAS
CLEANING
SYSTEM
PARTICULATE
STEAM
2.462
5.897
EXIT
GASES
0.015

Figure 24. Generalized mass balance for Andco-Torrax system. Units in Mg of steam per Mg refuse.

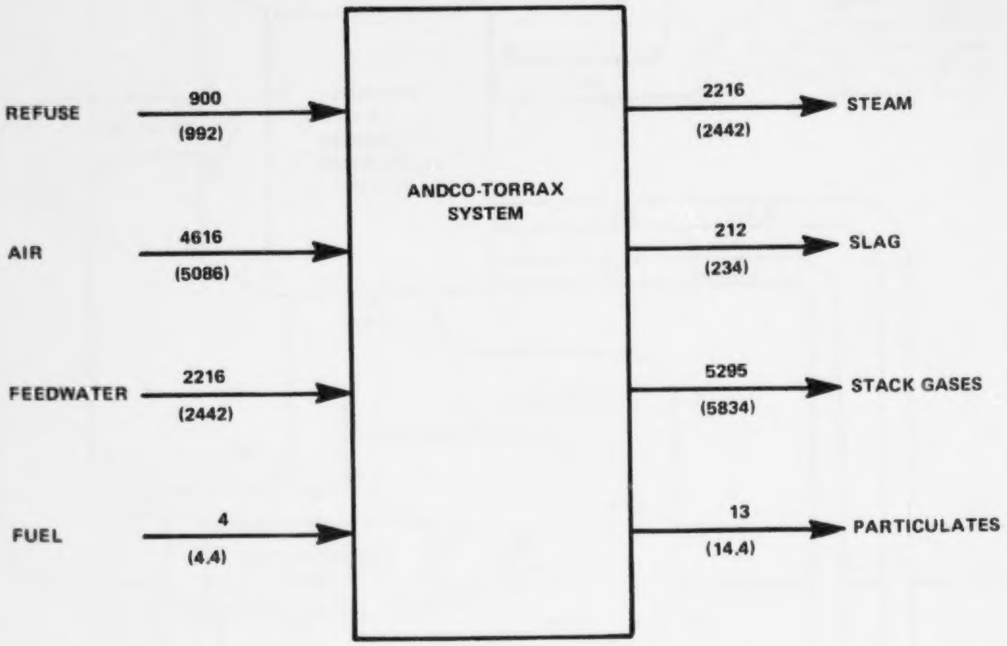

REFUSE
900
(992)
AIR
4616
(5086)
FEEDWATER
2216
(2442)
FUEL
4
(4.4)
ANDCO-TORRAX SYSTEM
2216
(2442)
STEAM
212
(234)
SLAG
5295
(5834)
STACK GASES
13
(14.4)
PARTICULATES

Figure 25. Mass balance summary for 900 Mg/d (992 TPD) Andco-Torrax system. Units in Mg/d (TPD).

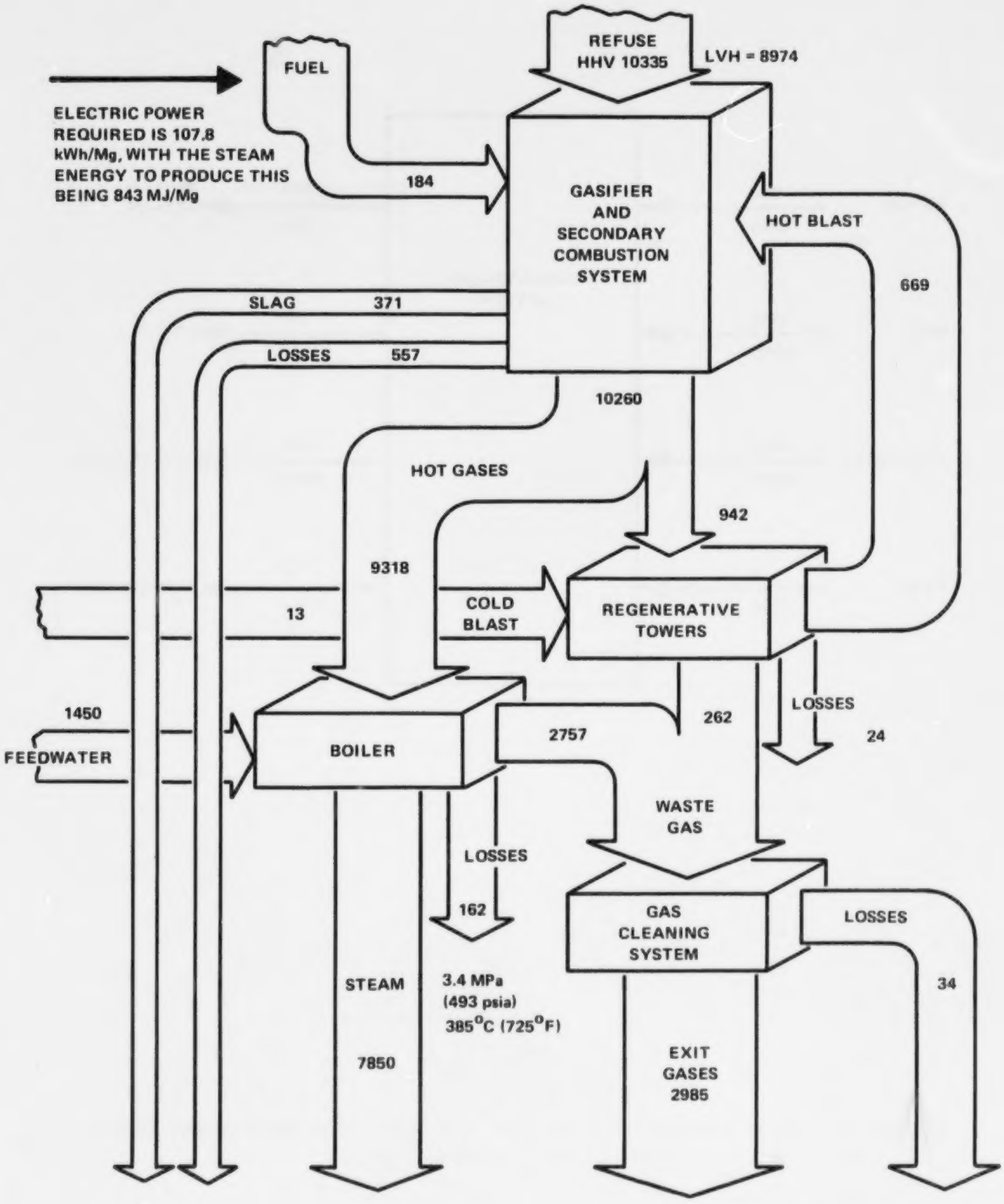

REFUSE
HHV 10335
LVH = 8974
FUEL
ELECTRIC POWER REQUIRED IS 107.8 kWh/Mg, WITH THE STEAM ENERGY TO PRODUCE THIS BEING 843 MJ/Mg
184
GASIFIER AND SECONDARY COMBUSTION SYSTEM
HOT BLAST
669
SLAG
371
LOSSES
557
10260
HOT GASES
942
9318
13
COLD BLAST
REGENERATIVE TOWERS
1450
FEEDWATER
BOILER
2757
262
LOSSES
24
WASTE GAS
LOSSES
162
GAS CLEANING SYSTEM
LOSSES
34
STEAM
3.4 MPa
(493 psia)
385°C (725°F)
7850
EXIT GASES 2985

Figure 26. Generalized (1-Mg refuse input) heat balance for Andco-Torrax System. Units in MJ/Mg refuse.

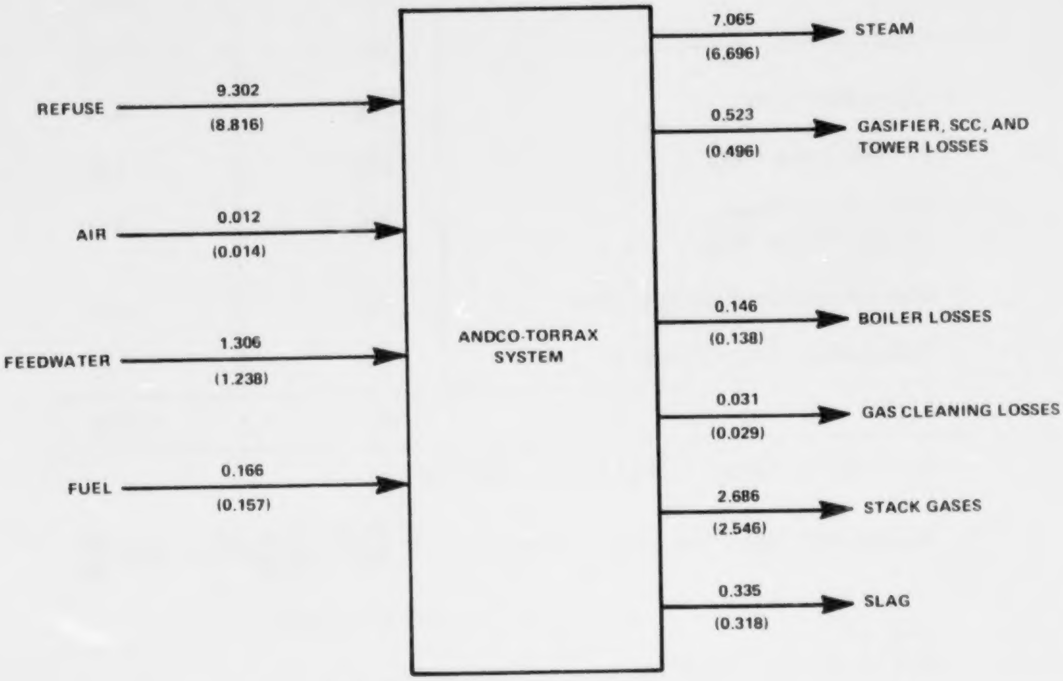

REFUSE
9.302
(8.816)
AIR
0.012
(0.014)
FEEDWATER
1.306
(1.238)
FUEL
0.166
(0.157)
ANDCO-TORRAX SYSTEM
7.065
(6.696)
STEAM
0.523
(0.496)
GASIFIER, SCC, AND TOWER LOSSES
0.146
(0.138)
BOILER LOSSES
0.031
(0.029)
GAS CLEANING LOSSES
2.686
(2.546)
STACK GASES
0.335
(0.318)
SLAG

Figure 27. Heat balance summary for 900 Mg/d (992 TPD) Andco-Torrax system. Units in TJ/d (10^9 Btu/day).

TABLE 21. MAJOR ELECTRICAL EQUIPMENT USE, 300 Mg/DAY (331 TPD) MODULE

Item	Power	
	kW	HP
System I.D. Fan	247	331
Primary Fan	62	83
Secondary Fan	309	414
Boiler Feed Pump	185	248
Open Water Pump Closed Water Pump	296	397
Electrostatic Precipitator	87	117
Peripheral Requirements	26	35
Total	1 212	1,625

Electrical input = 1212/0.9 = 1347 kW

$$\text{Equivalent Heat for Electric Power} = \frac{1347 \times 24 \times 3.6}{300 \times 0.46} = 843\ \frac{\text{MJ}}{\text{Mg}}$$

$$= 3.6\ \text{MJ/kWH}$$

Efficiency of Steam to Electric Power Used = 46%

both cases are given here so that the reader can make whatever comparisons he desires with other steam producers. Energy values are taken from Figure 26.

The conversion efficiency (ηc) is:

$$\eta c(\text{LHV}) = \frac{\text{energy in steam - energy in feed water}}{\text{Lower Heating energy in refuse}} = \frac{7850-1450}{8974} \times 100 = 71.3\%$$

$$\eta c(\text{HHV}) = \frac{7850 - 1450}{10335} \times 100 = 61.9\%$$

The net thermal efficiency (ηt) is based upon the amount of energy in to make the steam less the energy in product steam required to produce the electric power to drive the various pieces of equipment in the system. This is divided by the sum of energy in the incoming refuse, energy in supplementary fuel oil, energy in the water to the waste heat boiler, and energy in the secondary and primary combustion air. The value is given as

$$\eta t_{(LHV)} = \frac{\text{net energy out}}{\text{sum of energies in}} = \frac{7850 - 1450 - 843}{8974 + 184 + 13} \times 100 = 60.6\%$$

$$\eta t_{(HHV)} = \frac{7850 - 1450 - 843}{10335 + 184 + 13} \times 100 = 52.7\%$$

Shredding and processing the raw refuse may be desirable in order to recover the revenue-producing materials. Additional equipment will be required and could be amortized by the material-sale revenues. One method for simple processing of the entering refuse to recover some of the materials is to pass the raw refuse through a trommel such has now been installed in New Orleans (Ref. 7). This serves to break open bags, break glass so that it is sifted out by the trommel, and separate the smaller steel cans so they can then be recovered with a magnetic device. Such an arrangement could be considered for a large plant operation but is not included in the analysis for this report. A certain amount of glass is desirable in the refuse feed to assist in the slagging by lowering the melting point.

FACILITIES AND PROCESS EQUIPMENT PERFORMANCE

Equipment for a 900 Mg/d (1,000 TPD) plant has been priced based upon estimated costs by Andco and Parsons. Figure 28 shows a plan view of the plant including the various pieces of equipment that were described in the process diagram of Figure 23. In bringing together three such 300 Mg/d modules, the building will be extended in length and a raw refuse pit will be designed in the system to be used for feeding all three gasifiers. Alternative schemes to pit-and-crane raw refuse handling should be evaluated.

A more detailed analysis is required to determine the amount of refuse to be stored. Andco plans storage for as much as 3 days and this may be necessary where a reliable flow of steam is required without the use of much auxiliary oil-firing. Gasifier operation characteristics are such that it can be turned down by about 15% if the availability of refuse has decreased and more is not available for a period of time.

Figure 29 shows an elevation of the 300 Mg/d module. An emergency spill line, not shown, for emergency dumping of gasifier off-gas to an aspiration burner is to be included. It is estimated that for a 900 Mg/d plant with sufficient room for movement of trucks, dropping of refuse, and location of ancillary equipment, 32 376 m^2 (8 acres) of land may be needed.

The operation of the plant on an annual basis would require approximately 2 to 3 weeks shut-down for scheduled maintenance. In addition, there may be unscheduled down-time, with a total of scheduled and unscheduled down-time of approximately 4 to 5 weeks. This results in a utilization factor of approximately 90 percent, although 85 percent would be more in keeping with this type of high temperature equipment. Use of three modules adds a degree of redundancy and therefore more production reliability. Table 22 shows the summary of plant production flow rates. On a yearly basis, a utilization factor of 90 percent is used.

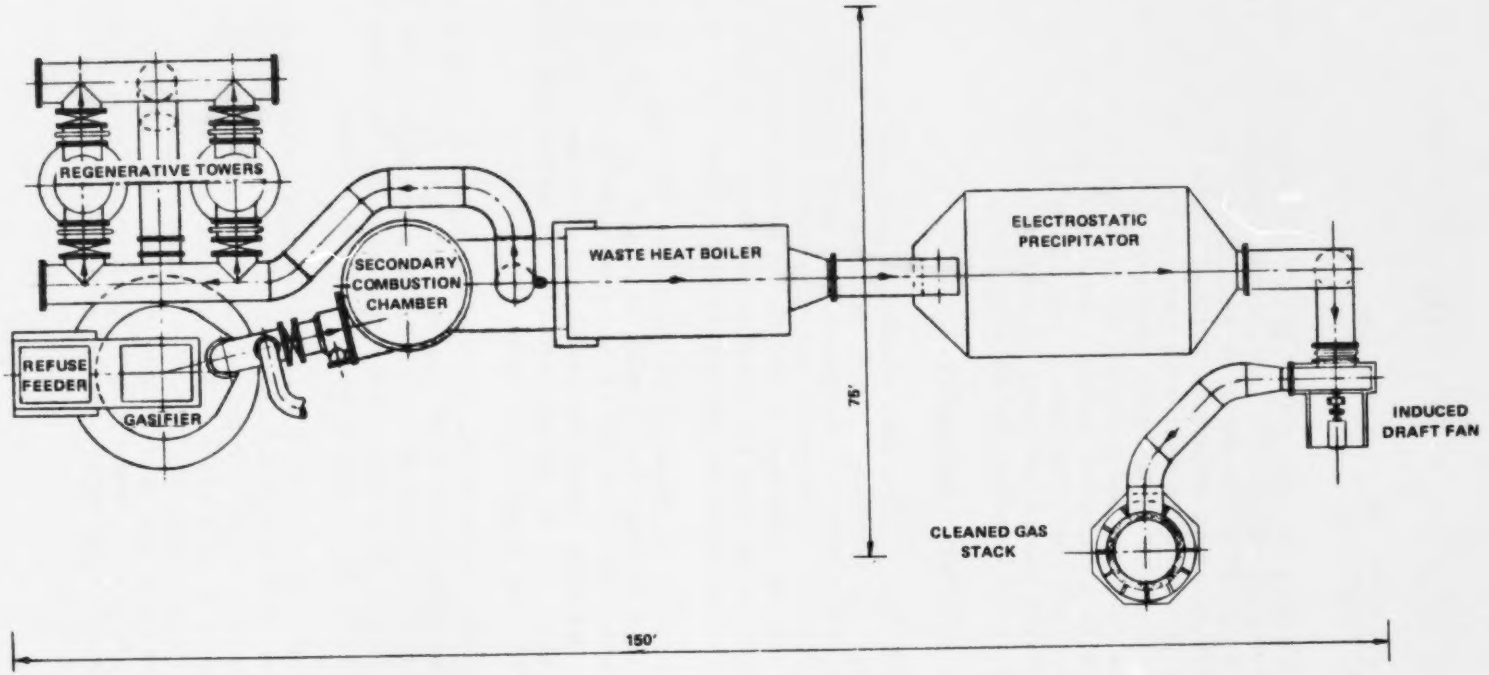

REGENERATIVE TOWERS
SECONDARY COMBUSTION CHAMBER
WASTE HEAT BOILER
ELECTROSTATIC PRECIPITATOR
REFUSE FEEDER
GASIFIER
75'
INDUCED DRAFT FAN
CLEANED GAS STACK
150'

Figure 28. General arrangement plan for 300 Mg/d Andco-Torrax system.

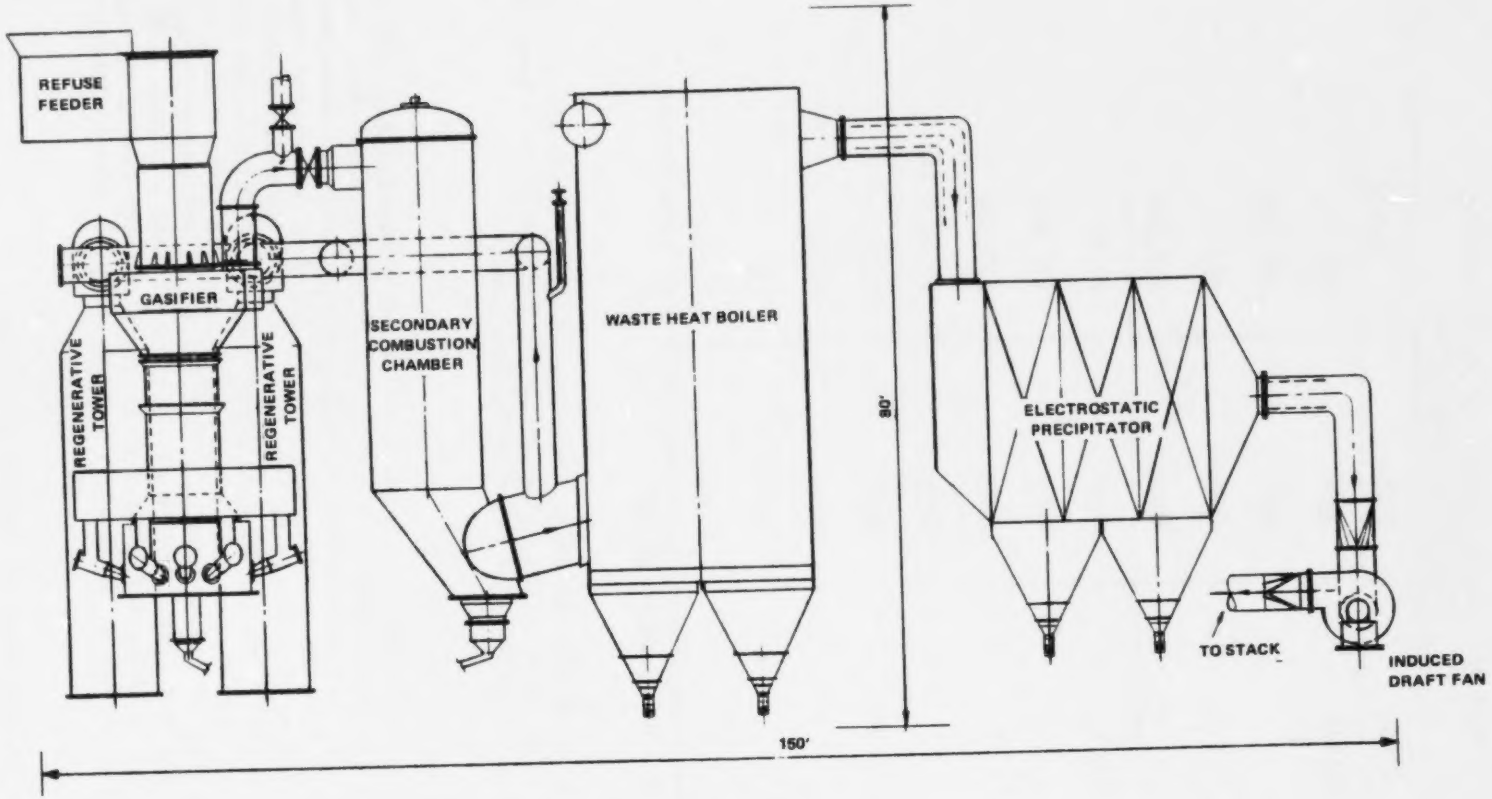

REFUSE FEEDER
GASIFIER
REGENERATIVE TOWER
REGENERATIVE TOWER
SECONDARY COMBUSTION CHAMBER
WASTE HEAT BOILER
80'
ELECTROSTATIC PRECIPITATOR
TO STACK
INDUCED DRAFT FAN
150'

Figure 29. Elevation of the Andco-Torrax system 300 Mg/d module.

TABLE 22. ANDCO-TORRAX 900 Mg/d (992 TPD) PRODUCTION FLOW RATES*

Item	Units	Amount
Refuse	Mg/d	900
	Mg/y	295 700
	Tons/d	992
	Tons/y	325,900
Steam	Mg/h	92.32
	Mg/y	727 800
	lb/hr	203,500
	lb/y	1.605×10^9
Residue	Mg/d	212
	Mg/y	69,600
	Tons/d	234
	Tons/y	76,800

*0.9 Utilization Factor

Details of much of the equipment are proprietary to Andco and not completely available for this report. The following discussion is a general description of the performance of major equipment items.

Gasifier

In the bottom, or hearth area, preheated air at approximately 1093°C (2,000°F) comes from the regenerative towers through a hot blast main into a circular bustle pipe. It then passes through a multiplicity of downcomer-tuyere arrangements into the hearth area to burn the char descending from the pyrolysis area. The major section of the gasifier shell is water cooled, resulting in a protective skull* of solidified slag being formed over the refractories in the hearth area. This skull protects the refractories from the high temperatures of approximately 1649°C (3,000°F) and corrosive action of the molten metals and slag. The molten slag flows into a quench tank that is periodically dumped, allowing discharge of the shattered glassy aggregate or frit while the pressure in the reactor remains slightly above atmospheric.

---

*A hardened layer of slag next to cooled refractory.

Quench water is continuously introduced to keep this part of the equipment cool. Refuse from the pit entering the top is fed into a feed hopper by the grapple bucket and then automatically fed from the hopper into the gasifier reactor vessel by a ram mechanism. The gasifier is approximately 2.8 m (9 ft) in diameter and 16.3 m (53 ft) high at the feed mechanism at the top and 4 m (13 ft) below floor level.

Moist refuse entering at the top of the gasifier moves downward past the gas exit area with a lantern-type of gas off-take. From this point down, the refuse dries and then, in the pyrolysis zone, is heated from 260 to 1093°C (500 to 2000°F), where the rate of decomposition to gases, oil, char, and ash increases with temperature. Various oils formed in the low temperature region of pyrolysis continue to pass down and are cracked into gases and char at the higher temperatures. Those particles of char and oil that are entrained in the hot gases are mostly scrubbed out by the descending refuse, thereby recycling down into the higher temperature zone. A portion of the char and ash particulates pass out with the off-gas.

The heat generated by the burning of char with the preheated air in the hearth area provides for the drying of the refuse, the heating of the refuse, heat losses through the walls, and melting of the slag. The heat of chemical reaction may be slightly endothermic. Most of the heat required is for raising the temperature and drying the refuse. Gases leave the reactor at 450° to 550°C (800° to 1,000°F).

Fuel Gas System

About 90 percent of the energy content of municipal refuse is contained in the gas stream that leaves the gasifier. This energy is in the form of combustible gases, vapors, and entrained particles, and as sensible and latent heat. The temperature of this gas is approximately 427°C (800°F). Complete combustion of this gas stream produces about the same volume of products of combustion per unit of heat released as would be the case with other gaseous fuels. Because of the high sensible heat content of the gas, it must be closely coupled with a combustion chamber. Other than a combustion chamber and steam generator, the products can be utilized if the gasifier is closely coupled to other apparatus such as cement kilns, lime kilns, or drying systems.

Composition of the combustible gas stream is dependent on the refuse mix, but should be approximately that which has been measured at the demonstration unit (Table 20). The higher heating value of the hot char-laden gas will be approximately 6.90 MJ/Nm^3 (175 Btu/SCF).

Secondary Combustion Chamber (SCC)

The combustible gas-vapor mixture from the gasifier is thoroughly mixed with a minimum of excess air and burned to completion in the secondary combustion chamber. The fuel gas mixture drawn out of the gasifier lantern section is typically at a temperature of 315° to 550°C (600° to 1,000°F). The fuel gas is mixed with ambient combustion air in a high energy mixing burner at the inlet to the secondary combustion chamber. Gas enters the SCC in a tangential fashion for high turbulence spiral action to further aid complete combustion. The thorough mixing, high temperature, and long residence time in the refractory-lined SCC insures complete combustion with a minimum of excess air (approximately 63 percent).

High temperatures maintained in the combustion chamber (1150 to 1260°C or 2,100 to 2,300°F) causes the fly ash and other inert carryover materials to melt, fuse, and be slagged out of the stream. Lower particulate and lower objectionable gaseous emissions are claimed as compared, for instance, with conventional incinerators. Andco indicates that smaller gas cleaning equipment is required to meet allowable emission codes.

Regenerative Towers

At the demonstration plant, a natural gas direct-fired, silicon carbide cross-flow shell and tube heat exchanger was used to supply the high temperature primary air to the gasifier. While this unit has proven reliable, the cost and the diminishing availability of natural gas make such a unit unattractive for commercial plants. Use of a regenerative type of heat exchanger results in energy and cost savings.

Two vertical refractory-lined steel shells, filled with checker-work refractory brick, are used as regenerative heat exchanger towers to recover a portion of the process heat for pre-heating the primary combustion air as shown in Figure 30. About 10% by volume of the hot gaseous products of combustion are drawn from the SCC and passed through the top of one of the two regenerative towers. The induced draft fan downstream from the electrostatic precipitator causes the flow. Refractories in the tower are heated to a temperature of approximately 1150°C (2,100°F) at the top and 260°C (500°F) at the base. The waste gas exiting the regenerative tower checker-work is returned to a duct at the inlet of the gas cleaning system (electrostatic precipitator). A modulated damper valve in the boiler exit duct controls the amount of gas used in heating the regenerative tower checkerwork. Combustion air, on being passed through the hot refractories, is preheated for the gasifier. The two refractory lined regenerator towers are automatically and alternately heated and cooled in predetermined controlled cycles. Refractory-lined and checker brick-filled regenerators of this type have long been used in iron, steel, and glass making.

During the "blast" cycle, the combustion products from the secondary combustion chamber are diverted to the second regenerative tower and ambient process air is introduced at the base of the fully heated regenerative tower, where it passes up through the checkerwork absorbing the stored heat. The exit temperature of the air from the checkerwork ranges from 980°C (1,800°F) to 1150°C (2,100°F). This preheated air then flows to the gasifier hearth. A constant primary air, or blast, temperature is maintained by blending the heated air with ambient air before introduction into the gasifier. Automatic sequencing of the regenerative towers is controlled by temperature sensors.

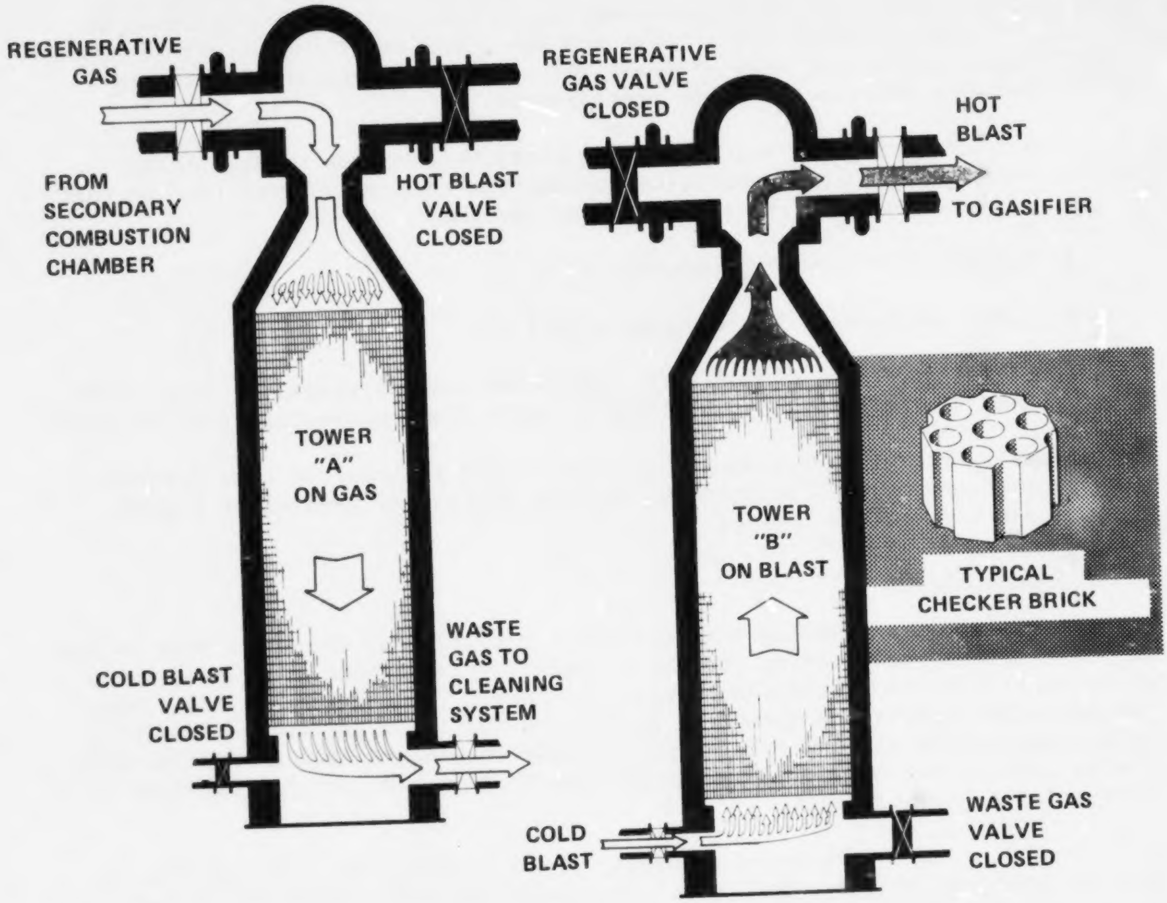

REGENERATIVE GAS
FROM SECONDARY COMBUSTION CHAMBER
HOT BLAST VALVE CLOSED
REGENERATIVE GAS VALVE CLOSED
HOT BLAST
TO GASIFIER
TOWER "A" ON GAS
COLD BLAST VALVE CLOSED
WASTE GAS TO CLEANING SYSTEM
TOWER "B" ON BLAST
TYPICAL CHECKER BRICK
COLD BLAST
WASTE GAS VALVE CLOSED

Figure 30. Schematic of regenerative towers.

Waste Heat Boiler

The major portion (90 percent) of the volume of combustion products drawn from the secondary combustion chamber passes through the waste heat boiler, which is a combination radiation-convection type. As much as 3 kg of saturated steam is produced for every kg of municipal refuse consumed in the Andco-Torrax System. Gases leave the waste boiler at approximately 300°C (592°F) and combine with flow of spent gases from the regenerative towers before entering the electrostatic precipitator.

It was determined by Andco that the waste heat boiler is physically smaller but equal in steam generation production to conventional incinerators of equal refuse capacity for the following reasons:

- Higher inlet gas temperatures.
- Lower gas volume due to lower excess air.
- Slagging of ash in secondary combustion chamber minimizes slag carry-over to the boiler, permitting use of a large convective tube section.

Additionally, boiler tube cleaning is simpler and is required less frequently than in the conventional incinerator boilers because of removal of a good deal of ash and soot in the SCC.

Gas Cleaning System

The waste gases leaving the regenerative towers and the waste heat boiler are combined before entering the gas cleaning system, which usually consists of an electrostatic precipitator, sized to handle the maximum gas flow from the secondary combustion chamber. Because of the lower gas volume resulting from lower excess air and a lower particulate loading, a smaller precipitator can be used in the Andco-Torrax system than that for conventional systems to meet emission requirements.

Depending on the emission requirements in a particular municipality, a wet scrubber may be preferred. Such equipment can offer installation economy, as well as being able to remove objectionable gaseous constituents in addition to particulates. Because of the acid gas content of the emissions, gases throughout the electrostatic precipitator are kept well above the dew point to prevent corrosion problems both in the precipitator and the stack attached downstream. Refuse contains a low sulfur content compared to other fuels and hence the SO_x formed is usually sufficiently low enough to meet emission standards in most areas. Because of the alkaline character of the ash, as much as 25% by weight being calcium oxide, a considerable amount of SO_2 will be absorbed in a highly turbulent, refuse fly-ash filled combustion chamber. Trace emissions measured will be discussed later. The normal dry gaseous principal components in the flue gas when processing 10.33 MJ/kg (4,445 Btu/lb) refuse are 80.4 percent nitrogen, 12.4 percent carbon dioxide, and 7.2 percent oxygen by volume. With moisture, by Parsons calculation, there is 68.2 percent N_2, 10.5 percent CO_2, 6.1 percent O_2, and 15.2 percent H_2O.

Process Residue

The slag formed in the hearth of the gasifier and the secondary combustion chamber are quenched, resulting in a black glassy aggregate or frit. A chemical analysis is described in Table 23. The particle sizes range from 0.4 to 6 mm with most at 2 mm. This material is passed into a slag holding tank, and several methods are available for transporting it from the tank. At the demonstration plant, the material flows into a slag pit and a front-end loader is used to carry it to a pile for later removal by truck. An automatic method would use drag and belt conveying transfer, with deposition being made at a continuous rate on horizontal or inclined belt conveyors feeding a vertical bucket elevator. The bucket elevator directs the material to external storage bins or stock piles for transport to suitable disposal areas on an as-needed basis. A third method is the pumping of a suspension of slag from the main pit to dewatering tanks. The suspended solids quickly settle out in the dewatering tank for removal by grapple bucket or drag conveyor system to a point of disposal. The conveying liquid is pumped back through the system from the dewatering tanks for reuse in the quench tanks.

TABLE 23. CHEMICAL ANALYSIS OF RESIDUE

Constituent	% by Weight
SiO_2	46.0
Al_2O_3	10.0
TiO_2	0.8
Fe_2O_3	10.0
FeO	15.0
MgO	2.0
CaO	8.0
MnO	0.6
Na_2O	6.0
K_2O	0.7
Cr_2O_3	0.6
CuO	0.2
ZnO	0.1
Total	100.0

bulk density 1.40 g/cm^3
true density 2.80 g/cm^3

Volume reduction to the slag residue from the raw refuse is approximately 95 to 97% and the weight reduction 80 to 85%, depending on the inert fraction in the refuse.

Industrial Refuse Capability

In addition to normal municipal refuse, the Andco-Torrax System is capable of handling other wastes, particularly those from industry. These wastes can be mixed with municipal refuse with minor changes to the equipment and the operating procedures.

Some of the tests at the demonstration facility include the following:

- Sewage sludge. Undigested sewage sludge with 78 percent water content was charged with the municipal refuse in quantities averaging 28.5 percent of the total 3.4 Mg/h (3.8 TPH) charge.
- Waste oil. Waste automotive lubricating oil was charged with municipal refuse in average quantities of 6.1 percent of the 4.0 Mg/h (4.4 TPH) charge.
- Combined sludge and oil. A test combining sewage sludge with waste oil and municipal refuse was accomplished. The total feed rate was 3.1 Mg/h (3.4 TPH) of which 30.1 percent was sludge and 3 percent was oil.
- Tires. Unshredded automotive tires were charged with the normal refuse. The average addition was 30 tires per hour or about 10 percent of the total 3.0 Mg/h (3.3 TPH) consumption.
- Polyvinylchloride (PVC). Bags filled with PVC plastic waste were charged with municipal refuse in amounts averaging 7 percent of the 2.9 Mg/h (3.2 TPD) charge.

In all cases no significant changes to the process operation were encountered. The maximum amount of admixture of special waste has not been determined.

ENVIRONMENTAL FACTORS

Emissions

Waste gas emissions from the Andco-Torrax system will be from a stack after passing through a gas cleanup system.

Each 300 Mg/d module will require a stack to handle about 57 700 Nm^3/h (35,600 SCFM) of gas at 260°C (500°F). Based on the Luxembourg design constraints, a 1.6 m (5 ft) minimum diameter (ID) stack would be required approximately 50 m (164 ft) in height. Grouping three flues in one stack would require a minimum 4.6 m (15 ft) diameter single stack.

Height restrictions are based on emission regulations as well as local requirements. Generally, regulatory agencies provide height restrictions that are a function of concentration per unit area per unit time as a result of stack emission rates. To appropriately size a stack for use in a specific site, the necessary local condition requirements should be provided.

Provisions are also made for venting pyrolysis gases from the gasifiers in the event of emergency shutdowns. For this purpose, a single gasifier that is being shut down could be vented to a manifold to allow for combustion of these gases in the adjoining systems. In the event of complete power failure, an externally ducted spill-stack is included with an aspirator burner.

A self-contained power unit should be provided for a plant this size to actuate the necessary hardware in an emergency situation. A diesel auxiliary power unit for a 300 Mg/d module would produce about 350 kW needed for cooling water systems, instrumentation, control, and lighting.

Representative sampling of waste gases exiting from the boiler and prior to gas cleaning has been conducted at the demonstration facility over several months. The following are typical values obtained from this sampling:

Cl (Expressed as HCl)--88 ppm (EPA sampling in a previous period indicated values as low as 13 ppm; it is expected that these differences are caused by fluctuations in refuse compositions.)

SO_x--125 ppm.

NO_x--115 ppm.

Organic acids--0.2-0.6 ppm.

Hydrocarbons--3 ppm.

Aldehydes and Ketones--0.02-0.40 ppm.

Particulates--In that only a spray tower was used, particulate matter was above emission standards at approximately 1.3 g/Nm^3 (0.5 gr/SCF). There were no unusual characteristics of the gas stream or particles that would interfere with the operation of an electrostatic precipitator, baghouse, or venturi scrubber to significantly reduce particulate matter, certainly below the federal EPA standard of 0.08 gr/SCF at 12% CO_2.

Water--The quench water used in the process makes contact with residues that contain no putrescibles, and hence no organics are added to this water. Suspended solids and pH measured at the demonstration plant were approximately 30-60 mg/dm^3 and 7.8, respectively. This waste water is of a quality which, together with the sanitary wastes from the plant, can be directed to city sewer systems.

ESTIMATED CONSTRUCTION AND OPERATING COSTS

Construction costs include land, site improvement, the Andco-Torrax pyrolysis system with its related equipment, contingencies, and engineering and construction fees. Operating costs are those needed for the functioning of the plant. Financial charges associated with the long term amortization of plant costs are included in the economic analysis.

Construction and Capital Cost

Construction Cost--

Table 24 presents a summary of the estimated construction cost for a 900 Mg/day plant in 1976 dollars. Equipment cost estimates shown include installation of a conventional system without site acquisition, preparation, and development costs. Also, it would not include offsite distribution of steam. Installed cost was estimated to be $26,160,000 in 1976 dollars.

TABLE 24. ESTIMATED 1976 CONSTRUCTION COST SUMMARY, 900 Mg/d (992 TPD)

Item	Cost ($000)
Land	200
Site Improvement	800
Andco-Torrax System:	
Gasifiers	10660
Regenerative Towers System	incl.
Secondary Combustion Chambers	incl.
Boilers	incl.
Gas Cleanup (ESP's)	incl.
Instrumentation/Controls, Cooling Tower, Piping, Pumps, Plant Air	6,500
Buildings	7,000
Other Items (crane, etc.)	1,000
Subtotal	26,160
Contingencies (10%)	2,620
Engineer & Construction Management*	1,850
Total	30,630

*Some engineering costs included in equipment costs.

Site acquisition, preparation, and development is based on a land area of approximately 32 000 m^2 (8 acres). The land to be acquired would generally be in an industrial area with a total cost estimated to be $200,000. Site preparation includes clearing, utilities, earth work, grading, paving, landscaping, and fencing, which would cost approximately $800,000.

Total construction cost was then estimated to be $30,630,000 in 1976 dollars.

Capital Costs--

To establish capital requirements, Parsons added interest during construction, start-up costs, and working capital to the construction costs of \$30,630,000. The individual items are given in Table 25, which shows the total estimated capital cost to be \$34,940,000 in 1976 dollars. Interest during construction is determined by using 8-1/2 percent of the construction cost for a period of one year. Start-up costs are based upon the fact that the plant on the average will only be operating 50 percent of the time for the first year, and the cost during that year in terms of capital will therefore be 50 percent of production related costs; this is one-half of \$2,161,000 or \$1,080,000. The working capital of \$660,000 is based upon 25 percent of the annual operating cost, which is shown later in this section to be \$2,740,000.

TABLE 25. 1976 CAPITAL COSTS, 900 Mg/d (992 TPD)

Item	Cost ($000)
Construction	30,600
Interest during Construction	2,600
Startup Costs	1,080
Working Capital	660
Total	34,940

Operating Costs

Operating costs include labor, electric power, heating fuel, maintenance supplies and replacement parts, water, residue disposal, insurance, and taxes. A management fee to an operating organization (or an imputed cost in the case of government operation to properly allocate expenditures for billing, management control, Engineering Department staff, etc.) would oftentimes be included, but has not been done here because of its highly variable nature. Table 26 shows a summary of the operating costs. Accurate maintenance costs will be developed as the Luxembourg installation becomes operational and on-stream for a period of time. Information compiled by Andco and data available from industry estimates suggest that for the maintenance of a 300 Mg/d plant the annual cost should be approximately \$225,000. For three modules, the cost would be \$675,000, consisting of \$387,000 for labor and \$288,000 for supplies and replacement parts. The labor portion is included in the separate labor estimates.

Fuel oil is used in three places, 2.18 dm^3/Mg for the slag trap, 0.44 dm^3/Mg for the main burner, and 2.18 dm^3/Mg for the combustion chamber slag trap. Total fuel oil use is 4.80 dm^3/Mg (1.15 gal/ton) or 1577 m^3/y. This represents 9,700 barrels per year, and with #2 distillate fuel at \$15 per barrel, the cost of fuel oil would be \$146,000.

TABLE 26. 1976 OPERATING COSTS, 900 Mg/d (992 TPD)

Item	Annual Cost ($000)
Labor	1,188
Electric Power	798
Heating Fuel	146
Maintenance Supplies and Replacements	288
Water	49
Residue Disposal	70
Insurance	201
Taxes	-
Total	2,740

The water required is approximately 3 percent makeup of 25 m^3 of water required per Mg (6,000 gal/ton). The annual makeup therefore is 0.03 x 25 x 900 x 365 = 246 000 m^3/y (65 million gal/yr). At \$0.198/m^3 (\$0.75 per thousand gallons), the annual cost of makeup water is \$48,750.

The cost of labor as presented in Table 27 is based on use of three shifts, with the number of people required being determined from Andco and Parsons estimates. It was estimated by Andco that for a 900 Mg/d plant, 40 to 45 individuals will be required over three shifts. Table 27 shows an estimate of 50 people over three shifts as determined by Parsons. Basic pay rates are typical for a major city in the United States. The total labor direct cost per hour amounts to \$370.50. Using 2,080 hours per year, the total cost is \$771,000 per year, to which overhead and fringe benefits (amounting to an additional 50 percent, or \$385,000) must be added. Overtime is estimated to be 3,000 hours at \$7 per hour with a 50 percent premium, or \$32,000/year. The total labor cost is therefore \$1,188,000 as noted in Table 26.

Electric power costs result from the use of approximately 1180 kW (see Table 21) associated with major electric equipment for each module. Total annual power amounts to 31.9 x 10^6 kWh/y, for an annual cost, based on 25 mills/kWh, of \$799,000. The use of 25 mills/kWh is suggested by Sussman of the EPA as an average value to be used in the United States. Electric power costs range from 10 to 40 mills/kWh with some special areas at 60 mills/kWh.

Residue disposal assumes no market for the frit. This is a conservative estimate since this material is sterile and can be used for a variety of purposes. Possible uses have been studied and evaluated, such as roadway aggregate, black color additive to terrazzo, shot blast media, and decorative panels.

TABLE 27. 1976 LABOR COSTS, 900 Mg/d (992 TPD), 3 SHIFTS

Job Description	Number of Positions	Basic Pay $/hr	Total Pay $/hr/Position
Superintendent	1	11.00	11.00
Chief Operator	8	9.00	72.00
Assistant Operator	12	7.50	90.00
Crane Operator	7	7.50	52.50
Mechanical	8	6.50	52.00
Shear Operator	1	7.50	7.50
Maintenance Mechanic	3	7.50	22.50
Electrician	2	7.50	15.00
Scale Clerk	2	6.50	13.00
Janitor	1	6.00	6.00
Laborers	3	6.00	18.00
Secretary/Records	2	5.50	11.00
Total	50		370.50

Until a definite market is established, it is estimated by Parsons that this residue will be sent to a closeby landfill at a cost of $1 per Mg. There is about 212 Mg/d of slag to be disposed, and therefore the total cost per year is $70,000.

General insurance amounts to 0.6 percent of the construction cost of $30,600,000 or $183,600. Added to this is personal hazard insurance at 1.5 percent of the direct payroll of $1,188,000, or $17,800, for a total insurance cost of $201,400.

From Table 26 the total operating cost for the plant is seen to be $2,740,000 per year.

ECONOMIC ANALYSIS

In this section, an analysis is given for the total unit cost to operate a 900 Mg/d Andco-Torrax system in terms of dollars per Mg or ton of refuse (or dollars per Mg or thousand pounds of steam). An amortization cost is included using an 8.5 percent interest rate over a 20 year lifetime after start-up. With a capital cost of $34,940,000, and an amortization factor of 0.10567, the capital recovery per year is $3,692,000. The annual operating cost from the previous section is $2,740,000 per year, which yields the total annual cost of operation of $6,432,000 shown in Table 28.

TABLE 28. NET COST (1976 DOLLARS) TO PRODUCT STEAM(1)
900 Mg/day (1000 TPD)(2) PLANT

Item	Units	Drop Charge(3)	Value
Capital Required	$	NA	34,940,000
Cost of Operation			
Amortization(4)	$/yr		3,692,000
O&M Cost	$/yr	NA	2,740,000
Total Cost of Operation	$/yr		6,432,000
Net Unit Cost(5) Based on Received Refuse	$/Ton refuse	0	19.73
		5.0	14.73
		10.0	9.73
	$/Mg refuse	0	21.75
		5.5	16.25
		11.0	10.75
Net Unit Cost(5) Based on Steam Produced	$/1000 lb steam	0	4.00
		5.0	2.98
		10.0	1.97
	$/Mg steam	0	8.83
		5.5	6.60
		11.0	4.36

Notes:
(1) Yearly value for steam is 727,800 Mg, or 1.604 x 10^9 lb (utiliz. factor = 0.9)
(2) Nominal value (900 Mg/d = 992 T/day).
(3) Drop charge is treated as a revenue and is in $/Mg or $/ton raw refuse.
(4) Amortization @ 8-1/2% for 20 yrs.
(5) Net unit cost includes credit for drop charge.

For the present analysis, drop-charges of 0, $5.5 and $11 per Mg (0, $5, and $10 per ton) are used. The effect of these values on the cost per unit of product or cost per weight of entering refuse was then determined.

Fron the previously given heat balance, there are 7.85 GJ of energy content in the steam per Mg of refuse, amounting to 7.065 TJ (6.70 x 10^9 Btu) per day. Also, 2.462 Mg of steam are produced per Mg of refuse, resulting in 727,800 Mg (801,800 tons) of steam per year, using a utilization factor of 0.9.

Table 28 shows net costs to produce steam for 900 Mg/d (992 TPD) Andco-Torrax system. It is interesting to note that with no drop charge, the cost to produce steam is $4.00/1,000 lb, which is not unreasonable in comparison with the cost to produce steam by other methods. With a $10 drop charge, the cost to produce steam is quite competitive at $1.97/1,000 lb.

COSTS AND ECONOMICS AS A FUNCTION OF PLANT SIZE

Plant sizes used for calculation purposes are based on the number of gasifier modules installed. With each module at 300 Mg/d capacity, cost calculations presented here include systems for:

One (1) module - 300 Mg/d (331 TPD)

Three (3) modules - 900 Mg/d (992 TPD)

Five (5) modules - 1,500 Mg/d (1,653 TPD)

Construction and operating costs for the 900 Mg/d (992 TPD) case are shown in the previous section. Because of the modular construction, the cost of the installed modular parts of the plant will vary linearly with the number of modules. The cost of buildings, the receiving pit, and the crane will vary approximately with the 0.6 power of the plant size. Cost of instrumentation/controls, cooling tower, piping, pumps, plant air and electrical systems will vary with approximately the 0.8 power of plant size. Land and site improvement costs are given as a 0.8 power variation with plant size.

Using Table 24 as a base, Table 29 shows construction cost estimates for alternative sizes of 1, 3, and 5 module size plants. Variation of the total cost is found to be proportional to the 0.83 power of plant size. Capital requirements for construction and startup are given in Table 30. Although different exponents are used for several elements, all costs for the 300 Mg/d and 1500 Mg/d cases were estimated by Parsons using the 900 Mg/d values as a basis.

Operating costs (O&M) shown in Table 31 vary linearly except for labor, where the number of personnel for each job description, as shown in Table 27 may not change. For those that change, only a minor increase or decrease occurs. The variation in labor costs from that calculated for the 900 Mg/d (992 TPD) was approximately 20% less for the 300 Mg/d (331 TPD) plant and 20% more for the 1500 Mg/d (1,653 TPD) plant.

It can be seen in Table 31 that the unit costs drop considerably with increase in plant size, graphically shown in Figure 31. With an increase in size from 300 Mg/d (331 TPD) to 1500 Mg/d (1,653 TPD), unit costs reduce by about 50%, and become almost constant for larger sizes than 1500 Mg/d (1,653 TPD).

TABLE 29. ESTIMATED CONSTRUCTION COST SUMMARY WITH PLANT SIZE ($000) 1976 DOLLARS

Cost Element	Plant Size (Mg/d)(1)		
	300	900	1500
Land	80	200	270
Site Improvements	310	800	1,130
Andco-Torrax System	3560	10 660	17 700
Gasifiers	incl	incl	incl
Regenerative Tower Sys.	incl	incl	incl
Combustion Chambers	incl	incl	incl
Boilers	incl	incl	incl
Gas Cleanup (ESP's)	incl	incl	incl
Instrumentation/Controls			
Cool. Tower, Piping, Pumps			
Plant Air	2,700	6,500	9,800
Other Items (crane, stack, etc.)	600	1,000	1,500
Building	3,600	7,000	9,500
Subtotal	10,850	26,160	38,100
Contingencies (10%)	1,090	2,620	3,800
Engineer & Construction Management(2)	820	1,820	2,900
Total	12,760	30,600	44,800

(1) One module processes 300 Mg/d.
(2) Some engineering costs included in equipment costs.

TABLE 30. 1976 CAPITAL COSTS ($000)

Cost Element	Plant Size (Mg/d)		
	300	900	1500
Construction	12,760	30,600	44,800
Interest during Construction	1,080	2,600	3,800
Startup Costs	740	1,080	1,730
Working Capital	410	660	900
Total	14,990	34,940	51,230

TABLE 31. NET UNIT COST (1976 DOLLARS) TO PRODUCE STEAM[1]

Item		Units	Plant Size (Mg/d)		
			300	900	1500
Capital Required		$	14,990,000	34,940,000	51,230,000
Cost of Operation					
Amortization[2]		$/y	1,584,000	3,692,000	5,413,000
O & M Costs		$/y	1,493,000	2,740,000	3,778,000
Total Cost of Operation		$/y	3,077,000	6,432,000	9,191,000
Steam Production Rate[3]		Mg/h (lb/h)	30.77 (67,800)	92.32 (203,500)	153.9 (339,200)
Net Unit Cost	Drop Charge				
	0	$/Mg Steam	12.68	8.83	7.58
	$5.5/Mg		10.45	6.60	5.35
	$11.0/Mg		8.21	4.36	3.11
	Drop Charge				
	0	$/1000 lb Steam	5.75	4.00	3.45
	$5/T		4.73	2.98	2.43
	$10/T		3.72	1.97	1.42

(1) Net Unit Cost includes credit for Drop Charge.
(2) Amortization is 8-1/2% over 20 years.
(3) On yearly basis, use 0.9 utilization factor.

AMORTIZATION 8-1/2%, 20 YEARS, UTILIZATION FACTOR 0.9; CREDITS, ALUMINUM $300/T, STEEL $40/T, DROP CHARGE AS NOTED, 1976 DOLLARS

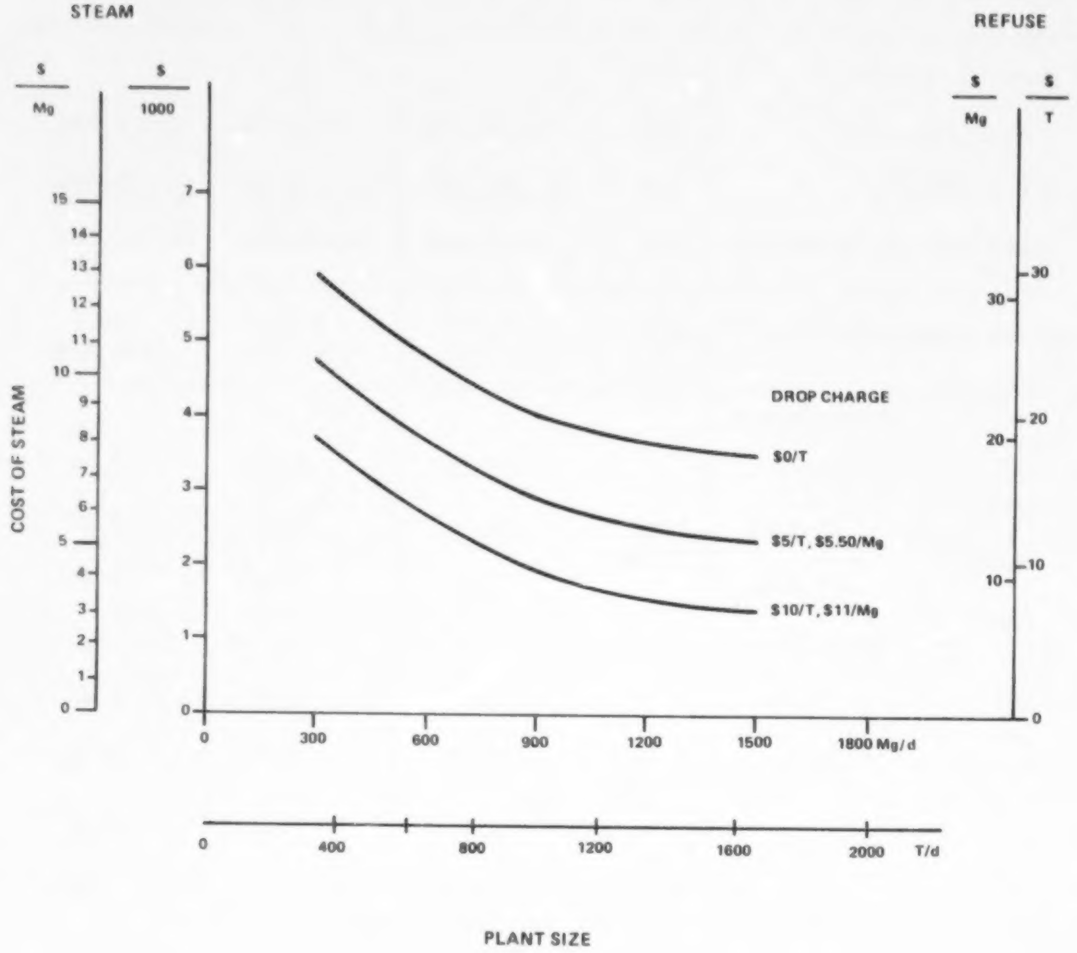


Figure 31. Net unit cost to produce steam with Andco-Torrax system.

SECTION 8

PUROX PYROLYSIS SYSTEM

INTRODUCTION AND SUMMARY

The Purox system, developed by the Union Carbide Corporation (UCC), converts solid wastes to a gas having an HHV of 11.81 to 15.36 MJ/Nm^3 (300 to 390 Btu/SCF). The principal unit is a vertical reactor for an oxygen-blown partial-oxidation pyrolysis process. A 181 Mg/d (200 TPD) demonstration plant has been successfully tested at South Charleston, West Virginia, using the municipal refuse collected in that area. Although first tested with raw refuse, operation with shredded refuse was found to be superior.

Refuse is injected near the top of the reactor, slowly descends as a moist feed, and a counter flow of hot gases then dries out the refuse and converts it to gases, liquids, and char in the pyrolysis zone. The char is burned with pure oxygen at the bottom (hearth) to produce an ascending mixture of hot CO_2 and CO that causes pyrolysis of the cellulose matter. Melting of inorganics results in a molten slag that runs off into quench water, forming a black glassy aggregate. The synthetic gas (syngas) leaving, after gas cleanup and cooling to remove oil, tar and ash, particulate matter, and moisture, is essentially free of nitrogen and consists mainly of hydrogen, carbon monoxide, carbon dioxide, and hydrocarbons. This syngas can be used directly as a fuel or can be converted to methane, methanol, ammonia, or a light hydrocarbon fuel. The Purox system is at such a state of development in converting municipal solid waste to a nitrogen free gas that it has now been offered with guaranteed operation as a commercial unit.

Construction cost for a 1381 Mg/d (1500 TPD) base plant in 1975 dollars was estimated at $53.75 million with capital requirements at $62.4 million. This included use of one spare Purox reactor element. Annual operating costs were estimated at $7.016 million. Construction costs were determined for two other sizes, 635 Mg/d (700 TPD) and 1905 Mg/d (2100 TPD) at $26 million and $74.6 million (using a spare reactor).

A net unit cost was determined for the base plant by using an 8-1/2% amortization rate and taking credit for steel recovered at $40/ton and aluminum recovered at $300/ton and a drop-charge. With no drop charge, the syngas would cost $3.30/million Btu; for a $5/ton drop charge, $2.53/million Btu; and for $10/ton drop charge, $1.84/million Btu.

Further processing of the syngas is required for subsequent uses. A compressor and drying system is needed before transporting the gas to the power plant at some distance, and a compressor is needed also to use the syngas in a gas turbine for producing electric power. For synthesis of methane, methanol, ammonia, or a light hydrocarbon oil from the syngas, a good deal of treatment is required to prepare the gas for chemical conversion. Some of these other gas utilization processes are discussed separately from the Purox system in Appendix C.

The three sub-systems are shown schematically in Figure 32. Both the front-end and gasifier are common to all plants, with the syngas being utilized in one of several processes, with one being shown. The gas is cool, clean, and dry and can be transported by pipeline to a customer (industrial heating or utility) several miles away.

Details are presented in the following sections of this report for a plant receiving 1588 Mg/d (1750 TPD) of municipal refuse over 6 days of each week. To maintain the necessary continuous operation of the Purox reactors, the equivalent of 6/7 x 1588 = 1361 Mg/d (1500 TPD) is used for process evaluation. Shredding, air classification, and materials recovery and storage are performed for 16 hours a day over 6 days, resulting in selection of process equipment that will handle the entering refuse at a rate of 99.8 to 109 Mg/h (110 to 120 TPH). Fuel gas is produced at the volumetric rate of 742 000 Nm^3/d (27.71×10^6 SCFD) and a heat content rate of 10.8 TJ/d (10.25×10^9 Btu/day). Daily quantities of ferrous metal and aluminum recovered are 111 and 5.4 Mg (122 and 6 tons) respectively.

The front end system is a separate unit and not part of the UCC-furnished Purox gasifier equipment. This process can be varied in terms of specific selection and arrangement of equipment. Presented is a Parsons system design based on experience in commercializing such a unit and where there is availability of equipment. It is similar to the Chicago supplementary process plant design reviewed in this report and differs by using one shredder per line, with addition of an aluminum separator.

In addition to the detailed information on construction, operating, and maintenance costs presented, an economic analysis by Parsons has been included to show the net costs of producing a product. This includes amortization at 8-1/2% over 20 years, revenues from recovery of steel and aluminum, and a range of refuse drop-charges from zero to $10/ton raw refuse. Readers can develop a set of net costs by substituting their own detailed local values for expenditures and potential revenues.

CONCLUSIONS

- Sufficient experience has been gained with operation of the South Charleston facility to conclude that the Purox gasifier is technically capable of being installed in any community desiring to convert wastes to a medium heating value gas. Any front end processing equipment deemed necessary for a given location can be considered as commercially available.

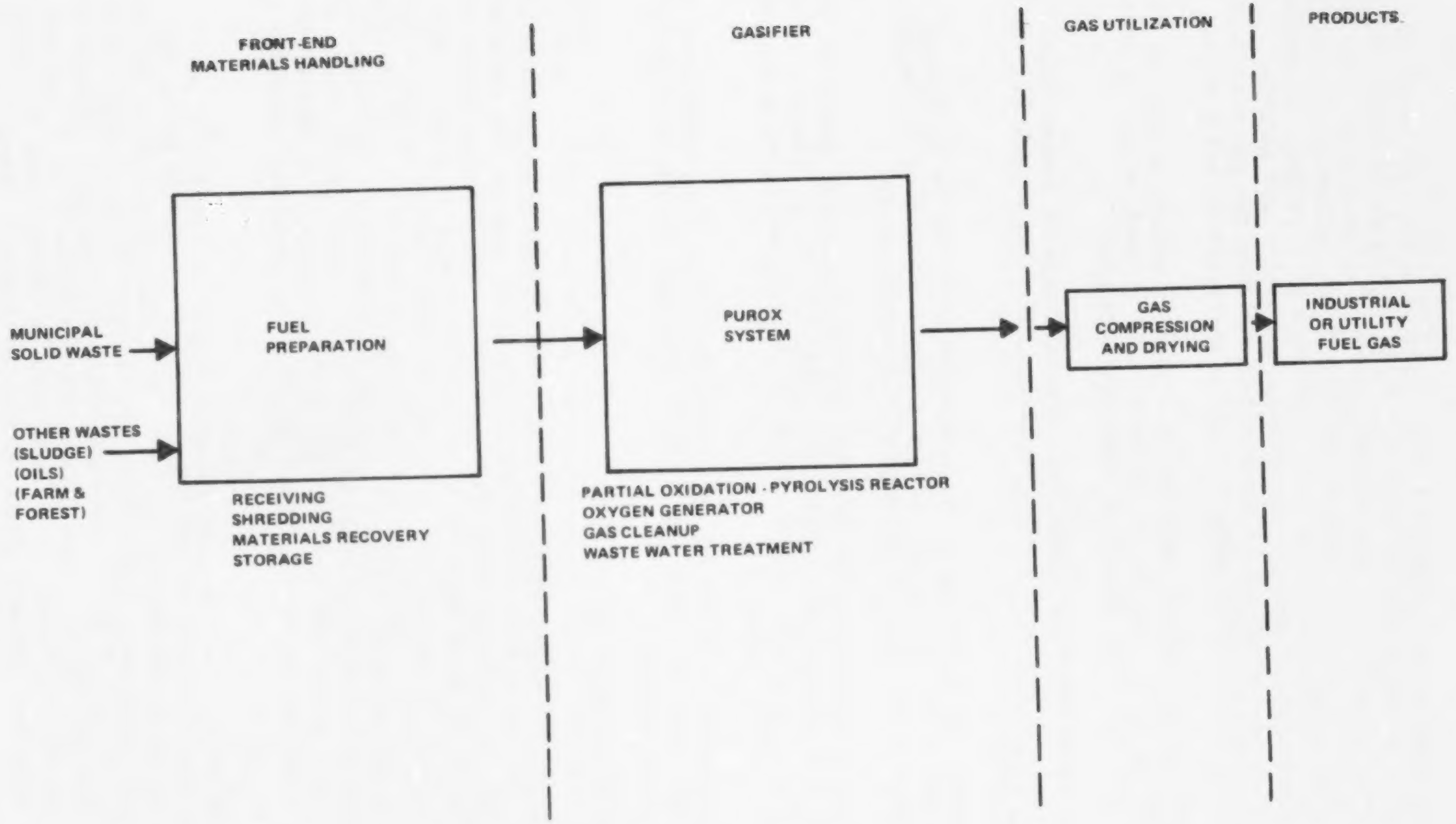

FRONT-END MATERIALS HANDLING
GASIFIER
GAS UTILIZATION
PRODUCTS
MUNICIPAL SOLID WASTE
OTHER WASTES (SLUDGE) (OILS) (FARM & FOREST)
FUEL PREPARATION
RECEIVING
SHREDDING
MATERIALS RECOVERY
STORAGE
PUROX SYSTEM
PARTIAL OXIDATION - PYROLYSIS REACTOR
OXYGEN GENERATOR
GAS CLEANUP
WASTE WATER TREATMENT
GAS COMPRESSION AND DRYING
INDUSTRIAL OR UTILITY FUEL GAS

Figure 32. PUROX gas generation and utilization.

- The synthetic gas produced is best used as a fuel for a utility or other customer having an existing furnace. Electric power can also be made for sale in a gas turbine combined cycle system. The gas, having a low nitrogen content because of the nature of the Purox process, is technically able to be converted to a variety of compounds. Of particular importance are methane, methanol, and ammonia. Critical steps in the synthesis of these materials from the gas must be experimentally investigated before accurate costs can be established.

- Product values should escalate in a similar manner as capital and operating costs, and it is concluded that current economics presented here are valid for projected comparison purpose.

- Below about 907 Mg/d (1000 TPD), the unit cost of syngas rises sharply and there is not much further economics of scale beyond 1361 Mg/d (1500 TPD).

- A variety of cellulosic or hydrocarbon wastes can be introduced along with MSW to the gasifier. Sewage sludge dewatered to 25% solids can be added to at least 10 percent of the weight of MSW.

- Similar emissions, except for SO_2, per heating value should be produced from burning the syngas in utility boilers as compared to natural gas. The sulfur in the syngas is low, but where necessary can be removed rather simply.

- With an organic content of approximately 50,000 BOD, condensate from the Purox gas will typically require treatment before introduction into sewer systems.

FRONT-END PROCESSING DESCRIPTION

Preparing raw municipal solid waste requires shredding to particle sizes from 10 to 20 cm (4 to 8 in.). All organic matter is sent to the gasifier. The process involves recovery of salable materials, with ferrous metals and aluminum chosen as the most marketable. The capital cost is greater than UCC has previously shown because of the aluminum recovery subsystem, which requires an air-classifier. Also, extensive air handling equipment is used to reduce dust and discharge relatively clean air to the surroundings. Although there are similarities to the Chicago supplementary fuel process plant, there are sufficient differences to describe this in relative detail. Aluminum separation, and small modularized storage bins are used; no secondary shredder is necessary.

For the purposes of design, the refuse received is assumed to have a composition as that presented by the EPA in Ref. 15. Table 32 shows the composition as given by EPA as well as Parsons' estimated values of HHV and moisture for each component. The average HHV is 10.77 MJ/kg (4,630 Btu/lb) and the moisture content 25.8%. This composition is a national average and representative for many major cities. Compositions measured in a specific community and somewhat different than those used in Table 32 can be substituted and subsequent dependent process variables and costs easily changed in the

TABLE 32. MUNICIPAL SOLID WASTE COMPOSITION, 1975

Component	Wt. %(1)	% Moisture(2)	Heating Value(2)	
			MJ/kg	Btu/lb
Paper	39.7	24.3	12.84	5,520
Glass	9.8	3.0	0.19	82
Metals (Total	9.6	6.6	1.65	709
Ferrous	(8.7)	-	-	-
Aluminum	(0.6)	-	-	-
Other Non-Ferrous (ONF)	(0.3)	-	-	-
Plastic	4.1	13.8	33.10	14,230
Rubber & Leather	2.7	13.8	19.65	8,450
Textiles	1.6	23.8	15.51	6,670
Wood	3.6	15.4	16.51	7,100
Food Waste	13.3	63.6	10.28	4,420
Yard Waste	14.1	37.9	9.37	4,030
Miscellaneous inorganic	1.5	3.0	4.77	2,050
	100.0			
Weighted Average		25.8	10.77	4,630

(1) From EPA report SW-161, modified by Parsons due to error in report table.

(2) Value from measurements on like components by Parsons.

several other sections of this report. UCC did not determine the actual composition of refuse at South Charleston. The sequence of operations is presented by a flow diagram in Figure 33, with Table 33 presenting flow rates for the numbered streams. First, municipal solid waste is delivered to a tipping floor where a front end loader pushes or places the waste onto one of two sunken conveyors. Two parallel lines of equipment are used, each with a capacity of 54 Mg/h (60 TPH), or a total of 109 Mg/h (120 TPH). The Purox

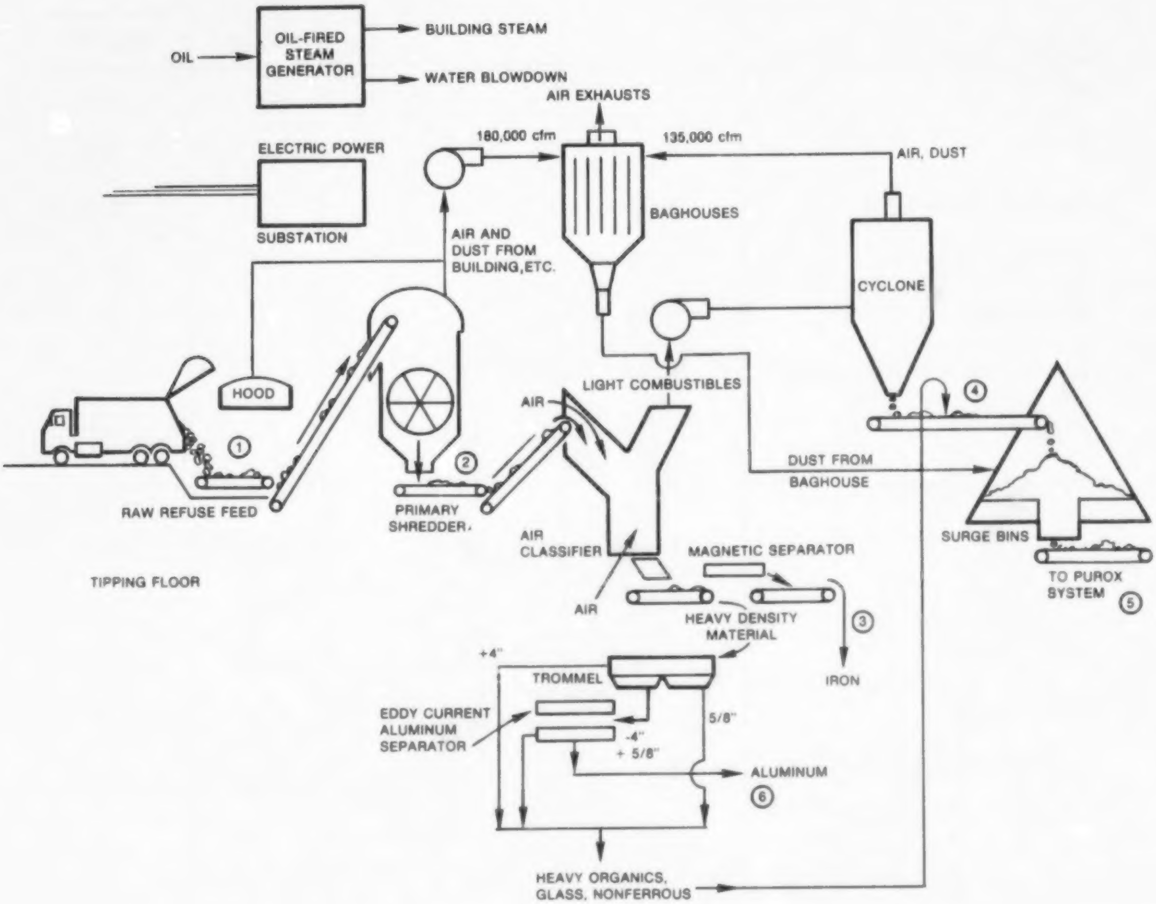

OIL
OIL-FIRED STEAM GENERATOR
BUILDING STEAM
WATER BLOWDOWN
AIR EXHAUSTS
ELECTRIC POWER
SUBSTATION
180,000 cfm
135,000 cfm
AIR, DUST
BAGHOUSES
AIR AND DUST FROM BUILDING,ETC.
CYCLONE
HOOD
LIGHT COMBUSTIBLES
AIR
①
②
③
④
⑤
⑥
RAW REFUSE FEED
PRIMARY SHREDDER
DUST FROM BAGHOUSE
AIR CLASSIFIER
MAGNETIC SEPARATOR
SURGE BINS
TO PUROX SYSTEM
TIPPING FLOOR
AIR
HEAVY DENSITY MATERIAL
IRON
+4"
TROMMEL
5/8"
EDDY CURRENT ALUMINUM SEPARATOR
-4"
+ 5/8"
ALUMINUM
HEAVY ORGANICS, GLASS, NONFERROUS

Figure 33. Flow diagram of Purox front end processing system.

TABLE 33. COMPOSITION OF MATERIALS IN FRONT-END UNIT STREAMS OF FIGURE 33. Mg/d (TONS/DAY)

Flowstream Figure 33	1	2	3*	4*	5*	6*
Component	(1) Receiving	Shredded Raw Refuse	Ferrous Recovery	Feed to Surge	Purox Feed	Aluminum Recovery
Organics	1060 (1,168)	1060 (1,168)	4.5 (5)	1055 (1,163)	1055 (1,163)	-
Ferrous Metals	122 (135)	122 (135)	111 (122)	12 (13)	12 (13)	-
Aluminum	8 (9)	8 (9)	-	2.7 (3)	2.7 (3)	5.4 (6)
Glass	131 (144)	131 (144)	0.9 (1)	130 (143)	130 (143)	-
Other Metals	4.5 (5)	4.5 (5)	-	4.5 (5)	4.5 (5)	-
Rock, Dirt, etc.	35 (39)	35 (39)	-	35 (39)	35 (39)	-
(Moisture) (2)	(340) ((375))	(340) ((375))	(4.5) ((5))	(336) ((370))	(336) ((370))	-
TOTALS	1361 (1,500)	1361 (1,500)	116 (128)	1239 (1,366)	1239 (1,366)	5.4 (6)
HHV, MJ/kg	10.77	10.77	0.51	11.77	11.77	-
HHV, Btu/lb	4,630	4,630	221	5,062	5,062	-

(1) See Table 32.

(2) Moisture is part of the components shown.

* Items in 3, 4, 5 and 6 are estimations. Aluminum recovery percentage from Combustion Power Co., Menlo Park, California.

System is to be operated over seven days with the equivalent of 1361 Mg/d (1,500 TPD) of delivered raw refuse. The front end plant is designed for receiving refuse over 6 days per week or 1588 Mg/d (1,750 TPD). The process equipment depicted in Figure 33 is to be operated over 16 hours or two shifts in each of 6 days/week, requiring an operational capacity of 100 Mg/h (110 TPH) or a design capacity of 109 Mg/h (120 TPH), 54 Mg/h (60 TPH) for each process line.

The raw refuse is conveyed to the shredders, which reduce the feed to less than 20 cm (less than 8 in.) sized particles. The discharge is then conveyed to an air classifier that is tuned (air velocity adjustments) to drop not only the steel cans but as much as 80% of the aluminum cans in the heavy fraction. The air classifier is used so that aluminum can be recovered. Otherwise, steel can be recovered directly from the shredder discharge with a magnetic belt. After recovery of the steel in the heavy fraction with a magnetic separator, the remaining material is passed through a trommel where a fraction in the size range of 10 to 1.6 cm (4 to 5/8 in.) is separated, containing primarily aluminum cans. This fraction is passed through an eddy-current aluminum can recovery unit. It was estimated that 67% of all the aluminum delivered to the plant is recovered. Table 33 shows the amounts of materials in each of the main streams in Figure 33. Some 5.4 Mg (6 tons) of aluminum and 111 Mg (122 tons) of steel are recovered daily. Revenues from aluminum recovered must more than pay for the capital and operating costs of the air classifier, aluminum separator, and associated equipment. The remaining material from the aluminum separator and trommel consisting of glass, other non-ferrous metals, and heavy organics are conveyed to surge bins along with the light fraction from the air-classifier.

The light fraction from the air classifier is separated from air in a cyclone. The air is discharged to the atmosphere after passing through a baghouse at the rate of 63.7 m^3/s (135,000 CFM). Using a separate fan, air is collected from various dust hoods in the process building, and passed through a baghouse at the rate of 84.9 m^3/s (180,000 CFM).

Actual feed to the Purox system from the surge bins is 1239 Mg/d (1,366 TPD) with an HHV of 11.77 MJ/kg (5,062 Btu/lb). Experience has demonstrated that large piles of moist shredded refuse in a bin left for several days may pack sufficiently to make retrieval with automatic equipment very difficult. Providing surge capacity for one or two days in relatively small amounts in multiple bins should present no retrieval problems. Each Purox gasifier module requires a nominal 317 Mg/d (350 TPD) feed. One surge bin is provided for each gasifier module and must provide a feed during the one day when no delivery of refuse is made to the plant, as well as the period in the third shift when the process equipment is not in operation. This amounts to 32 hours of storage. The bin has been designed for approximately 36 hours of storage or 476 Mg (525 tons). Tradeoff analysis for specific cases may lead to increased storage capacity depending on refuse delivery patterns and gas delivery requirements.

An oil-fired steam generator is used to heat the building and minor processing fluids.

The major pieces of equipment and their purpose are as follows:

- Weighing scales to measure delivery weights of refuse (not shown)
- Receiving or tipping floor where packer trucks drop their raw-refuse (municipal solid waste)
- Raw-refuse feed-conveyor to shredder
- Primary shredder that reduces raw waste to particle sizes less than 20 cm (8 in.)
- Air classifier to separate metals from the bulk of paper material as part of a heavy fraction for ease in recovery of aluminum
- Ferrous metals magnetic separator to recover steel cans and/or iron-based metals
- Rotary trommel to screen the air-classifier heavy fraction to provide high concentration of aluminum can material and reject -1.6 cm (-5/8 in.) (mainly glass) and +10 cm (+4 in.) (mainly wood, cardboard, etc.)
- Eddy current aluminum separator unit to recover a relatively pure aluminum can fraction
- Conveyor of aluminum recovery unit tailings to surge bin
- Main air classifier fan to pass air and light shredded fraction to cyclone
- Cyclone for de-entraining the light shredded fraction from the air classifier air stream
- Dust hoods in receiving and process building, and shredder and conveyor covers maintaining clean air conditions
- Dust hood fan for collection of dust and maintaining negative pressure in building
- Baghouses to filter dust from air-classifier air and dust hood air before discharge to atmosphere
- Surge bins for interim storage of all shredded refuse except for recovered ferrous metals and aluminum
- Ferrous metal and aluminum storage bins with bottom dump to truck loading
- Electric power substation for conditioning electric power from utility lines for use in front-end plant as well as gasifier system and, where necessary, gas utilization units

- Steam generator for heating buildings and process streams where needed

The energy flow in the incoming refuse is 1500 x 2000 x 4630 = 13.89 x 10^9 Btu/day (14.65 TJ/d) and the energy in the processed refuse feed to the Purox System is 1366 x 2000 x 5062 = 13.82 x 10^9 Btu/day (14.58 TJ/d). Practically all the organic matter is used, and only that which is trapped with the steel and aluminum is lost.

PUROX GASIFIER SYSTEM

The Purox gasifier is a vertical shaft furnace or reactor for the purpose of converting solid waste into a fuel gas by pyrolysis. This synthetic gas (syngas) consists primarily of hydrogen and carbon oxides with some hydrocarbons. There are three general zones of reaction in the vessel, consisting of drying, pyrolysis, and combustion/slagging, as shown in Figure 34.

The Purox gasifier concept was tested over a period of three years in a 4.5 Mg/d (5 TPD) pilot unit in the UCC laboratories at Tarrytown, New York. Encouraging test results with the pilot unit prompted UCC to build and operate a demonstration plant with a nominal capacity of 181 Mg/d (200 TPD) in South Charleston, West Virginia. That reactor is approximately 3 m (10 ft) ID and 9.1 m (30 ft) high, and has been operating since May, 1974. An extended test run for 3 months, 7 days per week, showed that the demonstration reactor operated well with shredded municipal refuse at full and part loading. Gases were found to have a greater volumetric heating value than was found at Tarrytown due to more hydrocarbons being generated. Shredding and magnetic separation of iron are all that is needed in a front end system. It is desirable to keep at least half the usual amount of glass in the reactor feed because of the need to reduce the melting point and viscosity of the molten slag formed in the char combustion zone. In addition, glass encapsulates metals in the residue.

The moist shredded refuse, with magnetic metals and some aluminum, enters at the top and slowly descends. A counterflow of hot gases, starting in the combustion zone at the bottom, dries the refuse, which then decomposes into synthetic gas, char, and organic liquids in the high temperature pyrolysis zone. Melting of inorganics and combustion of the char occurs in the hearth zone of the reactor, producing an ascending gas mixture of CO and CO_2. Pyrolisis-formed oil and char particles carried upward by the hot gases are mostly scrubbed out by the descending refuse and are thus internally recycled, with the oil cracking to gases and char. Relatively pure oxygen, from a cryogenic oxygen producer, is passed into the hearth to burn all the char. Molten slag is quenched to form a black glassy granular aggregate.

The heat of combustion of the char is sufficient to maintain a temperature of 1649°C (3,000°F) in the hearth for melting oxides, glass, metals, and other non-combustibles, and to provide the heat for pyrolysis reactions, heat-of-vaporization of water in the entering refuse, and heat losses from the vessel. The syngas produced is cooled to approximately 92-204°C (200 to 400°F) in drying the refuse.

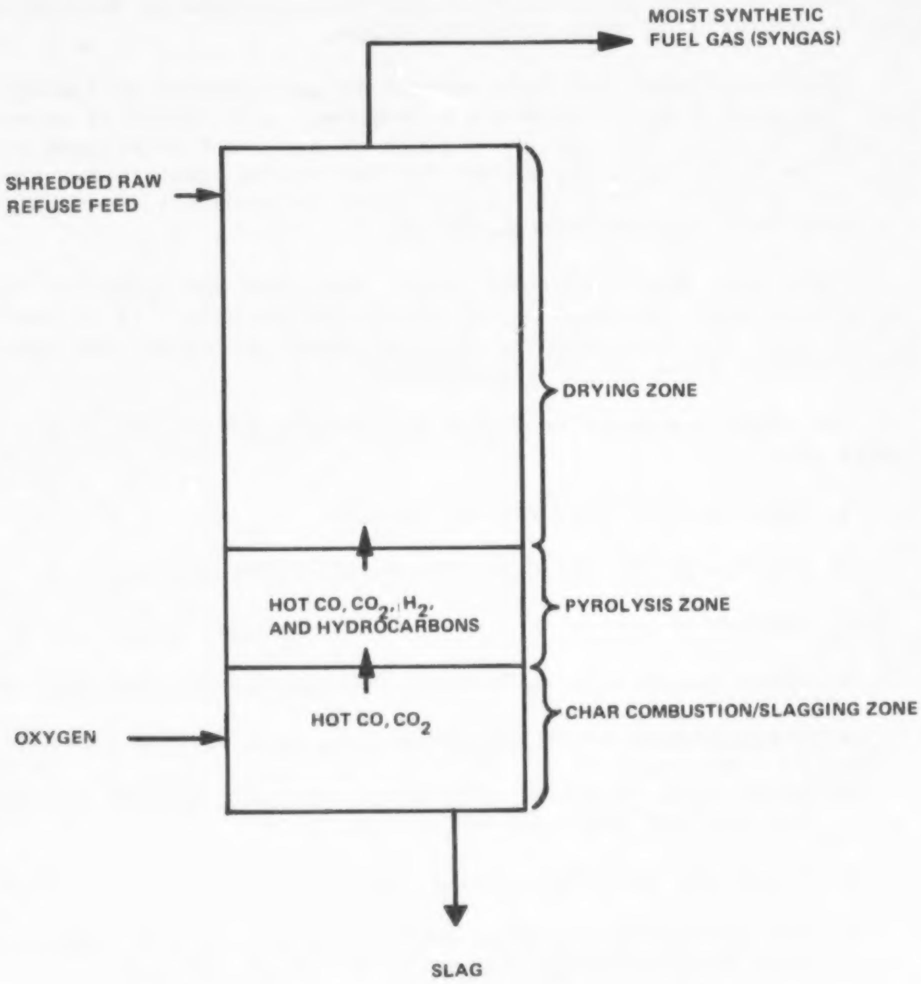

MOIST SYNTHETIC
FUEL GAS (SYNGAS)
SHREDDED RAW
REFUSE FEED
DRYING ZONE
HOT CO, CO_2, H_2,
AND HYDROCARBONS
PYROLYSIS ZONE
HOT CO, CO_2
CHAR COMBUSTION/SLAGGING ZONE
OXYGEN
SLAG

Figure 34. Schematic of Purox reactor.

An operational system for a community can use a 181 Mg/d (200 TPD) reactor module or a scaled-up 317 Mg/d (350 TPD) size. Actually, a module can operate over a wide feed-rate range. Use of the larger-sized module reduces the number of reactors required in processing refuse at delivery rates in the 907 to 1814 Mg/d (1000 to 2000 TPD) range.

Also associated with each reactor is gas clean-up equipment. Changes have been made from the original arrangement as a result of operational experience at South Charleston. A train of equipment associated with each reactor is shown in Figure 35, except for the oxygen plant, water treatment unit, and cooling tower, which are single units to serve all the modules. The water treatment unit is discussed separately.

For a 1361 Mg/d (1500 TPD) plant, four plus one spare 317 Mg/d (350 TPD) modules are used, as shown in the Facilities Section. It is Parsons judgment that a spare can be eliminated if operational experience can show a 0.9 utilization factor for a set of four modules.

The major pieces of equipment and their purposes are as follows: (See Figure 35)

- Inclined feed conveyor and leveler.
- Ram-feeder for injecting the mixed refuse material
- Reactor to convert the refuse to syngas and slag
- Water quench tank to solidify and shatter the slag into a frit
- Drag conveyor to transport the slag to a vehicle for hauling to disposal
- Water spray scrubber, with knock-out tank, to cool and remove char, tar, and ash from reactor off-gas
- Cooler for recycled scrubber water
- Wet electrostatic precipitator to remove fly ash, char, oil, and tar mist from the cooled and scrubbed reactor off-gas
- Solid-liquid separator system to separate oil and water from the char, oil, tar, and ash mixture to the reactor; recycle the scrubber water; and send excess water to waste water treatment
- Condenser to further reduce moisture content
- Combustor flare for emergency disposal of the synthetic gas
- UNOX or equivalent waste water treatment to condition water for acceptance in local sewage systems (required only if a Sanitation District does not allow high BOD discharge into sewage lines)

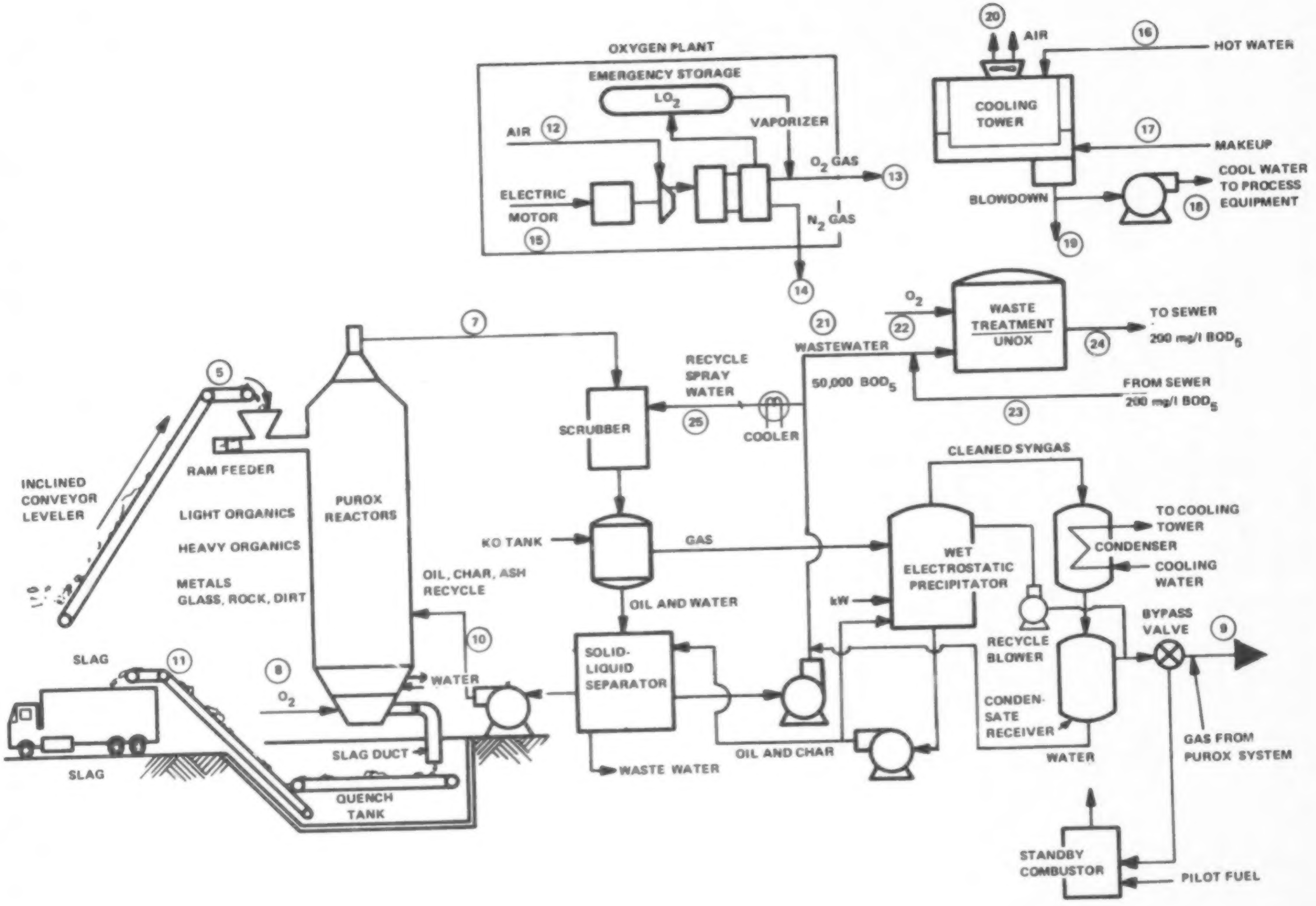

OXYGEN PLANT
EMERGENCY STORAGE
LO_2
AIR ⑫
VAPORIZER
O_2 GAS
⑬
ELECTRIC MOTOR
⑮
N_2 GAS
⑭
⑳
AIR
⑯
HOT WATER
COOLING TOWER
⑰
MAKEUP
COOL WATER TO PROCESS EQUIPMENT
BLOWDOWN
⑱
⑲
⑦
⑤
INCLINED CONVEYOR LEVELER
RAM FEEDER
LIGHT ORGANICS
HEAVY ORGANICS
METALS
GLASS, ROCK, DIRT
PUROX REACTORS
OIL, CHAR, ASH RECYCLE
⑩
WATER
⑧
O_2
SLAG
⑪
SLAG
SLAG DUCT
QUENCH TANK
RECYCLE SPRAY WATER
㉕
COOLER
SCRUBBER
KO TANK
GAS
OIL AND WATER
SOLID-LIQUID SEPARATOR
WASTE WATER
OIL AND CHAR
㉑
WASTEWATER
50,000 BOD_5
O_2
㉒
WASTE TREATMENT UNOX
㉔
TO SEWER
200 mg/l BOD_5
FROM SEWER
200 mg/l BOD_5
㉓
CLEANED SYNGAS
WET ELECTROSTATIC PRECIPITATOR
kW
TO COOLING TOWER
CONDENSER
COOLING WATER
RECYCLE BLOWER
CONDEN-SATE RECEIVER
WATER
BYPASS VALVE
⑨
GAS FROM PUROX SYSTEM
STANDBY COMBUSTOR
PILOT FUEL

Figure 35. Train of equipment for Purox gasifier system.

Quantities associated with the numbered streams connecting these pieces of equipment are given in Table 34.

TABLE 34. PUROX GASIFIER STREAMS*

Stream No.	Stream	Quantity		Other Information
		Mg/d	(TPD)	
5	Purox Feed	1239	(1366)	See Table 33 for Composition
7	Purox Reactors Off-gas	862 (950) Fuel Gas 382 (421) Water Vapor 32 (35) Char, Oil, Ash Particles 27 (30) Water Soluble Organics		Total Reactor Off-Gas 1303 Mg/d (1436 TPD)
8	O_2 to Reactors	254	(280)	Includes 11 Mg/d (12 TPD) N_2 + Ar
9	Purox Gas from Condensers	0.75×10^6 Nm^3/d (28.03×10^6 scf/d)		Saturated with water vapor at 38°C (100°F)
10	Char, oil, ash recycle	32	(35)	Mostly char
11	Slag	222	(245)	Includes oxidized metals and oxides inherent in paper, wood, etc.
12	Air to O_2 Plant	1451	(1600)	
13	Oxygen from Air Separation Plant	290	(320)	7/8 for Purox 1/8 for Unox
14	Nitrogen from Air Separation Plant	1161	(1280)	Gas discharge
15	Electric Power - Air Compressor	4060 Kw		For oxygen plant
16	Cooling Water Tower	0.85 m^3/s (13,500 GPM)		
17	Cooling Water Tower Makeup	0.02 m^3/s (320 GPM)		

* Values shown are based on information provided by Union Carbide.

continued

TABLE 34 (continued)

Stream No.	Stream	Quantity Mg/d	(TPD)	Other Information
18	Cooling Water to Process	0.85 m^3/s (13,500 GPM)		
19	Cooling Tower Blowdown	0.003 m^3/s (53 GPM)		
20	Air Exhaust/ Cooling Tower	0.06 x 10^6 Nm^3 (2.2 x 10^6 CFM)		
21	Waste Water	0.004 m^3/s (70 GPM) 27 Mg/d (30 TPD) organics		COD 40,000 to 60,000 mg/dm^3
22	Oxygen to Unox unit	36	(40)	
23	Dilution Water from Sewer	0.092m^3/s (1460 GPM)		BOD_5 = 200 mg/dm^3
24	Discharge to Sewer	0.096 m^3/s (1530 GPM)		BOD_5 = 200 mg/dm^3
25	Recycle Spray Water	0.013 m^3/s (200 GPM)		To off-gas scrubber

Gases leaving the reactor contain approximately 40% moisture by volume at a temperature of 93 to 204°C (200 to 400°F), with a higher heating value of the dry gas of approximately 14.57 MJ/Nm^3 (370 Btu/scf). The process conversion efficiency is estimated at 70% to 80%, depending on the moisture and materials content of the refuse. This efficiency does not account for the energy required for the oxygen plant, pumps, etc. An energy balance and overall efficiency showing the fuel energy needed for the electric power is presented later. Approximately 0.2 ton of O_2 per ton of solid waste is required for the gas generation process, plus an additional 0.027 ton of oxygen per ton of refuse for the waste water treatment process.

For 0.90 Mg (1 ton) of feed, 503.1 m^3 (18,780 SCF) of 14.57 MJ/Nm^3 (370 Btu/SCF) syngas are produced, for a total of 7.33 GJ (6.95 x 10^6 Btu) of energy in the syngas. It is of interest to note that over a wide range of refuse composition variations, the heating value of the gas and the quantity of gas produced per ton of refuse are inversely proportional. This means that the total heating value of the gas stream per unit weight of feed material remains relatively constant. Each 317 Mg/d (350 TPD) reactor and its gas cleanup equipment will produce 176 x 10^3 Nm^3/d (6.57 million dry SCF/day) of synthetic gas, with an energy flow of 2.56 TJ/d (2.43 x 10^9 Btu/day). The composition of gas leaving the system, shown in Table 35, was determined from tests by Union Carbide using municipal solid waste, at approximately 25% moisture, from South Charleston.

TABLE 35. TYPICAL DRY PUROX SYNTHETIC GAS COMPOSITION (1)

Gas Constituent	% by Volume
H_2	24.0
CO	40.0
CO_2	24.0
CH_4	5.6
C_2H_2, C_2H_4 $^{+(2)}$	5.4
N_2 + Ar	1.0
	100.0

(1) Gas actually leaves saturated with moisture at 38°C (100°F).

(2) C_2H_2 0.7, C_2H_4 2.1, C_2H_6 0.3, C_3H_6 0.2, C_4^+ 1.6, oxygenated HC's 0.2.

The feed material can be shredded refuse with only iron removed, or the shredded combustible fraction following air classification and removal of other revenue-producing materials. A few percent increase of inorganic feed changes the off-gas composition insignificantly according to tests run by Union Carbide at their Tarrytown pilot unit. Parsons estimate that the addition of biodigested sewage sludge will add a solids content that is approximately 50% organics and 50% ash with a higher heat content of 10.70 MJ/kg (4600 Btu/lb). Up to 15% by weight of sludge has been acceptable for design. Undigested sludge solids contain only 25% to 37% ash and have a higher heat content of 16.28 MJ/kg (7,000 Btu/lb) as measured by Parsons. Digested sludge dewatered to 75% moisture will increase the moisture content of the final sludge-solid waste mix by 6% to 7%. The mixed feed will then contain approximately 32% to 36% moisture; up to 45% moisture of mixed feed is technically acceptable. Increased moisture requires an increased amount of oxygen in the combustion zone of the reactor to provide additional heat for drying and maintenance of proper temperatures throughout the reactor. A corresponding increase in CO_2 occurs. Approximately 0.05 to 0.07 ton of oxygen is required per ton of refuse to provide the heat necessary to evaporate the moisture in refuse with a moisture content of 25% to 32%.

The total heat generated in the combustion zone can be accounted for by the following items requiring heat:

(1) Vaporization of moisture in the waste feed.

(2) Pyrolysis reactions.

(3) Heating and melting of the inorganic residue

(4) Heat losses from reactor vessel.

(5) Sensible heat in the off-gas.

In tests at South Charleston, contaminants were measured in the syngas after passing through the scrubber, electrostatic precipitator, and condenser. The NO_x content was not measurable, being less than 1 ppm. The HCl was measured at less than 1 ppm, having been absorbed by the scrubber water. H_2S was measured at levels between 300 and 600 ppm. One ppm or less of carbonyl sulfide (COS) was detected. A solid particulates level was measured at 0.159 g/Nm^3 (0.067 gr/SCF). Contaminants measured are shown in Table 36.

TABLE 36. CONTAMINANTS IN SYNGAS FROM PUROX SYSTEM AFTER GAS CLEANUP[a]

Component	Amount
Fly Ash	125 ppm (0.159 g/Nm^3, or 0.067 gr/SCF)
Sulfur as H_2S[b]	300 to 600 ppm
Water[c]	6% by volume
HCl	1 ppm
NO_x	1 ppm

[a] After the condenser; value will drop after glycol dryer.

[b] Measurement of COS showed 1 ppm or less.

[c] Water is contaminant if the gas is piped a considerable distance

This gas requires additional treating before methanation, methanol synthesis, or ammonia synthesis in catalytic converter systems. If the Purox gas is to be used directly in a power plant, but needs to be transported in a pipeline, even if only several hundred feet, much of the moisture must be removed, as described later.

Molten slag is collected in a pool at the bottom of the hearth. At the opening of the hearth to the quench tank, a small weir allows a pool to form that protects the hearth. After spilling over the weir, the slag falls through a slag pipe into quench water. A drag conveyor moves the shattered glassy slag aggregate up an incline to a conveyor and then to a truck for removal to landfill or storage. The slag has potential for such uses as roadbed fill, concrete block manufacture, or asphalt aggregate.

The amount of slag will vary depending on the extent of inorganic solids separation at the raw refuse shredding and separation plant. For the case of a feed with the ferrous fraction removed, the amount of slag generated is approximately 17% of the feed weight. The volume reduction of raw refuse to this residue of glassy aggregate is about 98%.

Approximately 0.26 m^3/min. (70 gpm) of waste water with a BOD of 40,000 to 60,000 mg/dm^3 is purged from the water/solids separator, equaling the amount of condensate formed from moisture in the Purox reactor offgas. This can be sent directly to a sewage line if allowable by the particular community sanitary district. If not, a waste water treatment unit will be needed to reduce the organic content to approximately 200 mg/dm^3. Included in Figure 35 is a Unox unit to be furnished along with the Purox gasifier system. Oxygen from the air separation unit is used at the rate of 36 Mg/d (40 TPD) to sustain aerobic digestion of the organics. For biodigestion to proceed satisfactorily, the purge stream is diluted 20 to 1 with sewage water from the nearest trunk line. Discharge from the digester back to the sewage line is at the rate of 5.79 m^3/min. (1530 gal/min) with a 200 mg/dm^3 BOD. This water treatment unit is included in the schedule of equipment. Alternative water treatment methods are briefly discussed in the section dealing with environmental assessment.

The Unox waste water treatment system consists of covered multi-stage biodigestion reactors in which oxygen is fed co-currently with the waste water. Pumping costs for the sewage and installation of a 7948 m^3/d (2.1 MGD) treatment unit adds considerable expense to the plant as well as requiring an additional 10 110 m^2 (2.5 acres) of land. Alternative methods for treating the relatively small waste water stream have been reviewed by Parsons such as reduced pressure stripping, carbon adsorption, or high pressure wet oxidation. A careful assessment is required of these alternative waste water treatment systems to ascertain their costs and performance. For this report, the Unox system is used because of its widespread acceptance and availability.

An energy balance, on a daily basis, for the front end plus the Purox system shows:

Purox Gas Energy Flow	10.94 TJ (10.37 x 10^9 Btu)
Raw Refuse Energy Flow	14.65 TJ (13.89 x 10^9 Btu)
Electric Power*	2.74 TJ (2.60 x 10^9 Btu)
Fuel Oil & Gasoline for Operation	0.26 TJ (0.25 x 10^9 Btu)

The net thermal efficiency of the Front End (FE) plus Purox system (Px) is:

$$\eta t\ (FE + Px) = \left(\frac{10.37 - 2.60 - 0.25}{13.89}\right) 100 = 54.1\%$$

---

* Calculated at 10,000 Btu/kWh.

The conversion efficiency of energy in product from energy in raw refuse is:

$$\eta c\ (FE + Px) = \left(\frac{10.37}{13.89}\right) 100 = 74.6\%$$

PUROX SYNGAS USE OR CONVERSION

The nitrogen free syngas produced in the Purox process can be converted to methane, methanol, ammonia, or used as a fuel in the generation of heat or electric power. Neither of the two other gas-producing partial oxidation pyrolysis systems that have reached demonstration or semi-commercial status using municipal solid waste feedstock (Andco-Torrax and Landgard, which are air blown) produced a gas suitable for conversion to NH_3, CH_3OH, or CH_4. There are some other concepts that have been tested in small or bench scale units to produce gases, but none of these appear technically or economically feasible at present. This section describes primarily the preparation of Purox gas for use as a fuel gas.

The simplest and most cost effective utilization method for the product is to construct the plant near a large fuel gas user, such as a utility power plant, and pipe the gas directly to the furnace as a primary or supplementary fuel. Other uses of the syngas are presented in detail in Appendix C. Five means of utilization are defined:

(1) Syngas For Delivery to Customers: Setting up a compressor station, dryer, and pipeline not included in equipment to supply syngas to a power plant.

(2) Conversion to Methane: Upgrading the syngas catalytically to pipeline quality for introduction into an existing gas utility pipeline distribution system.

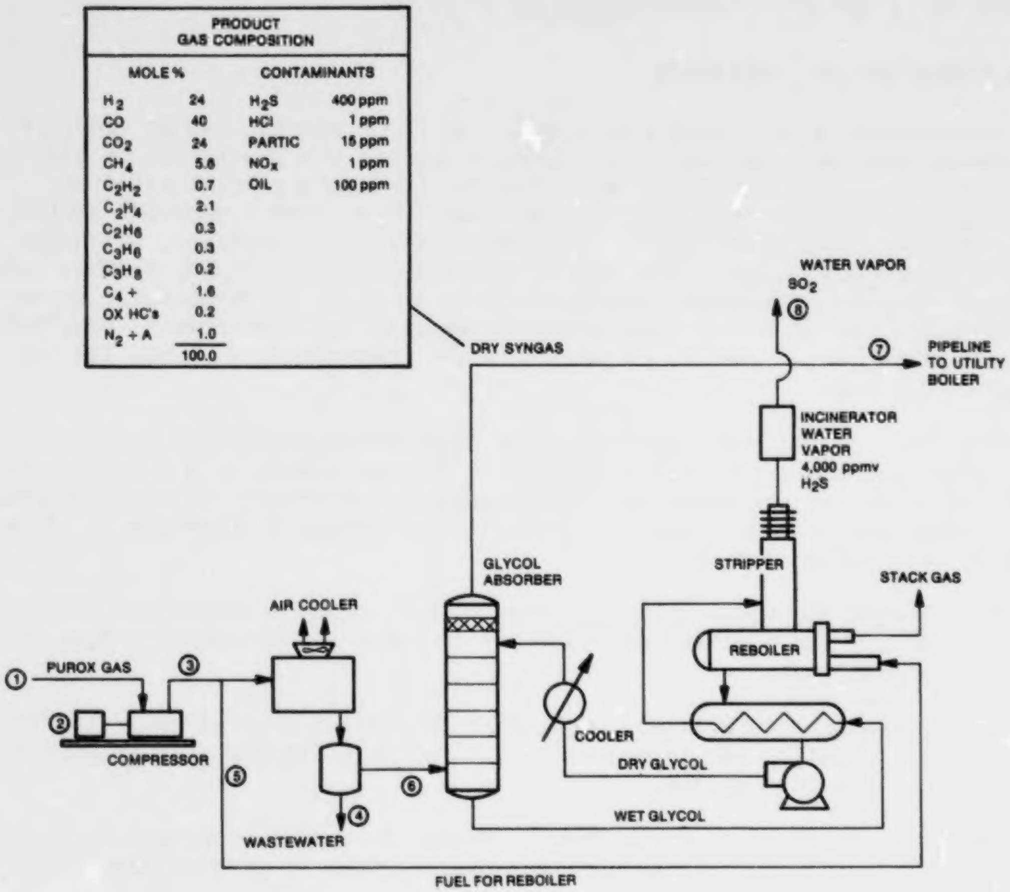
(3) Generation of Electric Power: Using the syngas as a fuel in a conventional gas-turbine combined-cycle system to produce electric power.

(4) Conversion to Methanol: Converting the syngas catalytically, wherein a product is derived that has value as a storable fuel for use in peaking power gas turbines, as an example.

(5) Conversion to Ammonia: Converting the syngas to pure hydrogen, and, with purified nitrogen from the oxygen plant, the mixture is transformed catalytically to ammonia.

To transport the gas by pipeline to a customer requires dehydration to prevent ice formation in the winter or liquid condensation during other times of the year. The most important factor is the proximity of a power plant or an industrial plant that has a long term demand for the syngas.

A flow diagram of the gas drier unit is shown in Figure 36. The gas is compressed to 446 kPa (50 psig) and first passed through an air cooler where



PRODUCT GAS COMPOSITION

MOLE %		CONTAMINANTS	
H_2	24	H_2S	400 ppm
CO	40	HCl	1 ppm
CO_2	24	PARTIC	15 ppm
CH_4	5.6	NO_x	1 ppm
C_2H_2	0.7	OIL	100 ppm
C_2H_4	2.1		
C_2H_6	0.3		
C_3H_6	0.3		
C_3H_8	0.2		
C_4 +	1.6		
OX HC's	0.2		
N_2 + A	1.0		
	100.0		

DRY SYNGAS
WATER VAPOR
SO_2
⑧
⑦
PIPELINE TO UTILITY BOILER
INCINERATOR
WATER VAPOR
4,000 ppmv H_2S
STRIPPER
STACK GAS
GLYCOL ABSORBER
AIR COOLER
REBOILER
① PUROX GAS
②
③
COMPRESSOR
⑤
COOLER
DRY GLYCOL
⑥
④
WASTEWATER
WET GLYCOL
FUEL FOR REBOILER

Figure 36. Gas compression and drying for piping to utility power plant.

approximately two-thirds of the water is condensed, collected, and pumped to the Unox water treatment unit. The gas is then scrubbed with triethylene glycol to further dehydrate the Purox gas. In winter, the dew point of the gas is reduced to -26°C (-15°F) and in the summer, 7°C (45°F). Some of the Purox gas, 8.8 x 10^3 Nm^3/d (0.33 x 10^6 SCFD), is used as fuel in the reboiler-stripper element of the dryer. The flow rate of dry gas is 744 x 10^3 Nm^3/d (27.71 x 10^6 SCFD), having an energy content of 10.82 TJ (10.25 x 10^9 Btu).

In the process of absorbing moisture, some of the H_2S will be absorbed by the glycol and then released in the stripper with the water vapor. A small burner will be required to convert the H_2S to SO_2. Emissions to the atmosphere will be 6.8 kg/h (15 lb/hour) of SO_2 and 454 kg/h (1000 lb/hour) of moisture for the plant. If this emission rate is not acceptable, a small caustic scrubber can be used to remove the H_2S from the stripper emissions.

Power required for the compressor is 3750 kW based on a 446 kPa (50 psig) discharge pressure. This pressure is minimal for an 8 to 10 km (5 to 6 mile) pipeline of approximately 20-inch diameter to a utility boiler. A higher pressure would reduce the pipe size, but increases the power required. A cost tradeoff analysis is required to determine the optimum pressure and pipe size for the particular application chosen. A pipeline to the customer is not included in costs of construction shown later.

The gas to be delivered to a utility boiler will contain approximately 200 to 400 ppm H_2S. A recent study associated with a power utility showed that this would produce 60 to 75% less SO_2 emissions than the corresponding fuel oil being replaced. For certain industrial purposes, where H_2S cannot be tolerated in the fuel gas, a simple Stretford scrubber system would be added to remove the sulfur and put it in solid form, which can be stored and sold when a sufficient amount accumulates.

Table 37 shows quantities and characteristics for several of the streams in Figure 36. Stream 7 is passed into a pipeline for transport to a utility or industrial furnaces.

FACILITIES

Descriptions are presented here for facilities recommended by Parsons to convert solid waste to syngas for use in a utility power plant or for chemical synthesis. The process for recovering resources from solid waste is described in the flow diagram, Figure 33. Figure 37, Solid Waste to Syngas Conversion Facility - Perspective View, shows an architectural perspective of a facility. Whether the gas is piped as a fuel to a utility or to a chemical conversion plant is not of concern in this section; the user of the gas is presumed to receive the gas at the plant property line in either case. Included in the facility are ferrous metal and aluminum recovery systems. Equipment noted is for purposes of typical design and cost estimation. Similar equipment is available from several manufacturers and final selection would be based on competitive bidding to a set of specifications.

TABLE 37. PUROX GAS COMPRESSION AND DRYING*

Stream No.	Stream	Quantity	Other Information
1	Gas from Purox System	753 x 10^3 Nm^3/d (28.03 x 10^6 dscf/d)	500 ppm H_2S 10.94 TJ/d (10.37 x 10^9 Btu/d)
2	Compressor Power	3400 kW	
3	Compressor Discharge	Same as 1, above, at 446 kPa (50 psig)	
4	Condensate from Air Cooler	19.3 dm^3/min. (5.1 gpm)	Varies with air temperature.
5	Fuel for Reboiler	8.8 x $10^3 Nm^3/d$ (0.33 x 10^6 SCF/d)	
6	Gas to Glycol Absorber	757 x $10^3 Nm^3/d$ (28.2 x 10^6 SCF/d)	
7	Gas to Pipeline	744 x $10^3 Nm^3/d$ (27.71 x 10^6 SCF/d)	400 ppm H_2S 10.82 TJ/d (10.25 x 10^9 Btu/d)
8	Stripper Emissions	454 kg/h (1000 lb/hr) water vapor and 6.8 kg/h (15 lb/hr) SO_2	H_2S is burned to SO_2

* Based on calculations at Parsons

Capacity Analysis

The referenced flow diagram was developed showing material quantities based on receipt of 1361 Mg/d (1,500 TPD) of solid waste into the system. It is dictated by several pertinent factors listed below, but not included are those related to the particular customer and the refuse character and amounts for a specific community over several seasons.

The syngas generators for the process are constructed in 317 Mg/d (350 TPD) capacity modules. The expected performance of these modules is such that four of them would be able to convert nominally 1270 Mg/d (1,400 TPD) of processed feed material from the raw refuse. The nature of the syngas generators is such that for best efficiency and least unit operating cost, they should operate continuously at design capacity. Solid waste collection is conducted on a 6-day-per week basis for this report and the front-end processing plant design and costs are predicted on operating two 8-hour shifts per day, 6 days per week, with the third shift and Sundays being utilized for maintenance operations. The required 1588 Mg/d (1,750 TPD) of raw refuse processing 6 days per week can be accomplished by two parallel processing lines with a

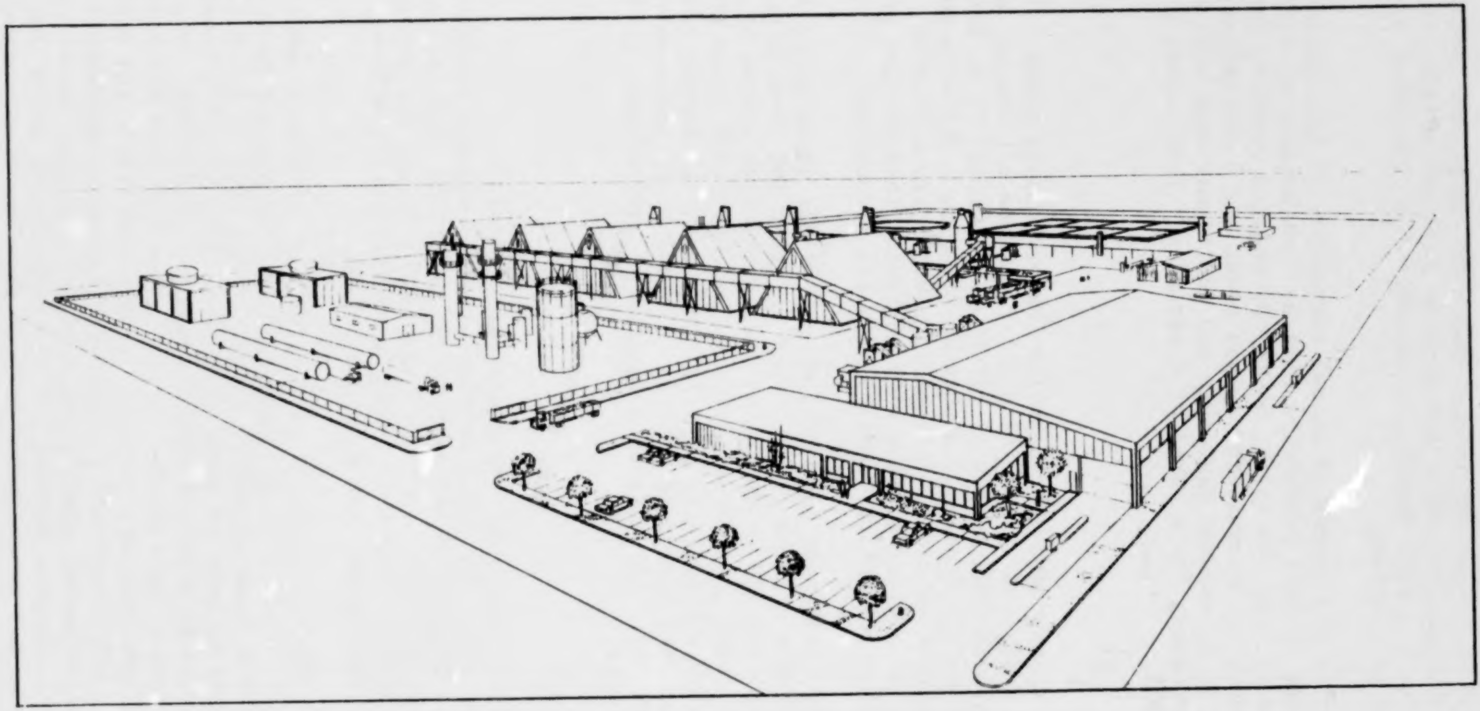


Figure 37. Perspective view of solid-waste-to-syngas conversion facility.

nominal capacity of 54.4 Mg/h (60 TPH) each. This will permit the installation of shredders at about the smallest size that provide good reliability and that can be coupled with other material handling equipment of a class that will function with a minimum of problems.

It is assumed that in the course of annual operations of the front-end processing plant, 3 weeks of full production will be lost because of scheduled maintenance requiring more than one shift, or to unscheduled downtime for unforeseen causes. In addition, because the syngas plant has 5 modules with only 4 operating at a time, .t is assumed that only one additional week will be lost due to unforeseen causes, for a total of 4 per year. This yields a plant utilization factor of 92%.

Site Characteristics

Figure 38 shows a recommended site plan for the processing plant. The dimensions shown, with a minimum of 30 m (100 ft) clearance all around, plus room for expansion, indicate that a plot of 347 by 250 m (1,140 ft by 820 ft), or approximately 87 000 m^2 (21.5 acres), should be procured. The site must be accessible by a road that is capable of handling heavy truck traffic. The road should also be on, or shortly connect with, arterial road(s) that provide access of solid waste collection vehicles from all directions.

The site must be provided with electric power that has capacity to 20,000 kV-A, 60 Hz, 3 Phase, with a minimum of 4160 volts. Water and sewer capabilities are needed for supplying and draining the fire protection system at a maximum of 3.78 m^3/min. (1000 gpm) in emergencies. Normal plant usage would not exceed 2 271 m^3/d (600,000 gpd) for cooling tower makeup, process steam, housekeeping, sanitation, and some dust control. In addition, there must be access to a sewage trunk line that carries a minimum of 5.29 m^3/min. (1400 gpm) during the daily cycle.

Front-End Processing Plant

Front-End Processing Plant Floor Plan and Equipment Layout--

Figure 39 shows the front-end building plan with the process equipment layout. The plant is composed of three major areas under one roof, and a fourth outside the building. Under roof are the tipping floor, the processing area, and the support services area that contains administrative offices, locker and lunch rooms, wash rooms, and maintenance shop.

The tipping floor receives the solid waste from the collection vehicles and provides the means for storing it and feeding it to the process equipment at the desired rate. The minimum clearance height to the roof is 6.1 m (20 ft). The floor shown will be able to store as much as 1361 Mg (1500 tons) of raw refuse (piled 3 m or 10 ft high), or about one day's production. The tipping floor is under roof to provide the receiving and handling operations protection from wet or windy weather, to permit control of litter and dust during these operations, and to provide a reasonable aesthetic appearance to enhance the external environmental quality for a refuse handling operation. The tipping floor area is unheated but has a large ventilating system for dust control and for removal of air contaminants emitted from the trucks and other

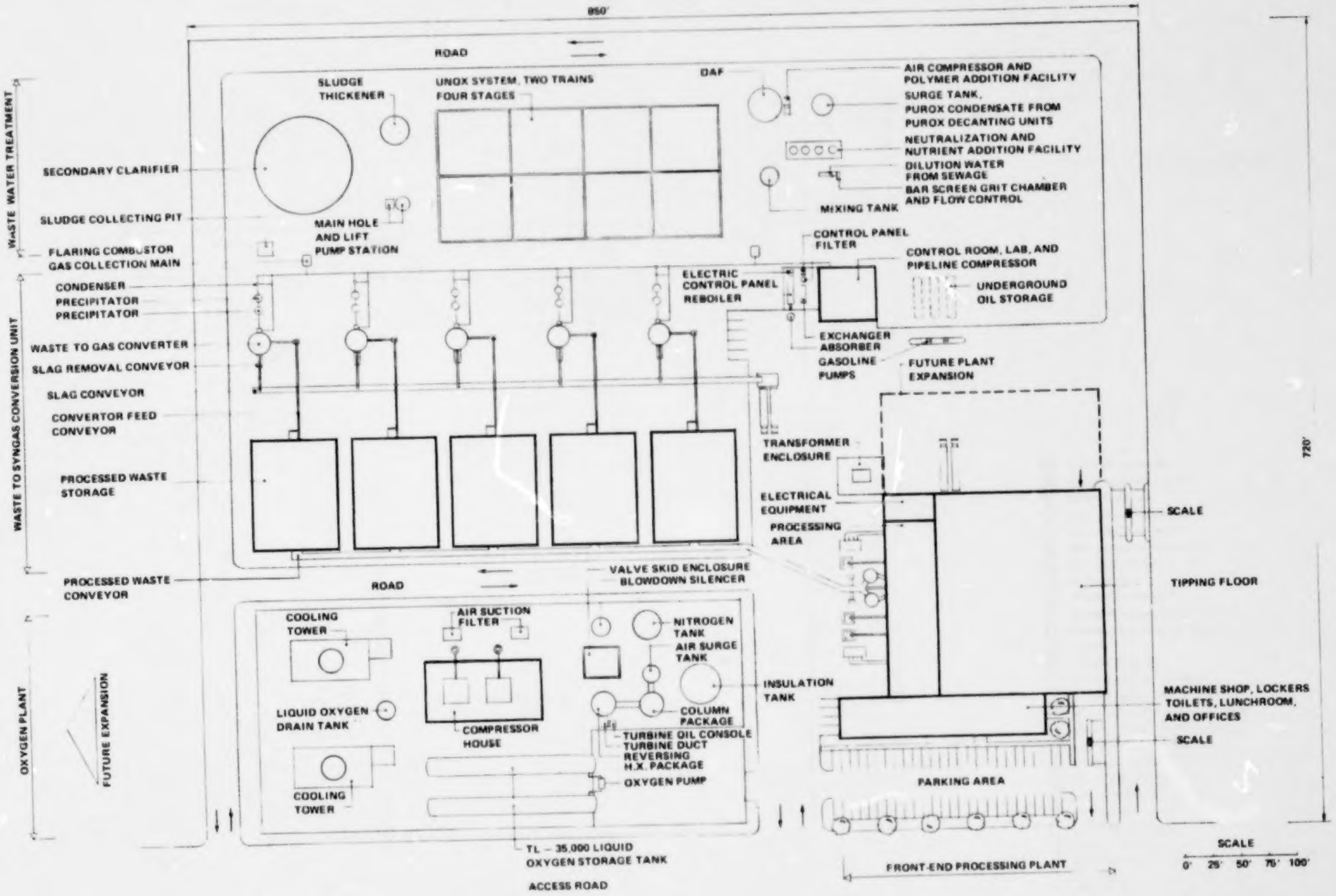
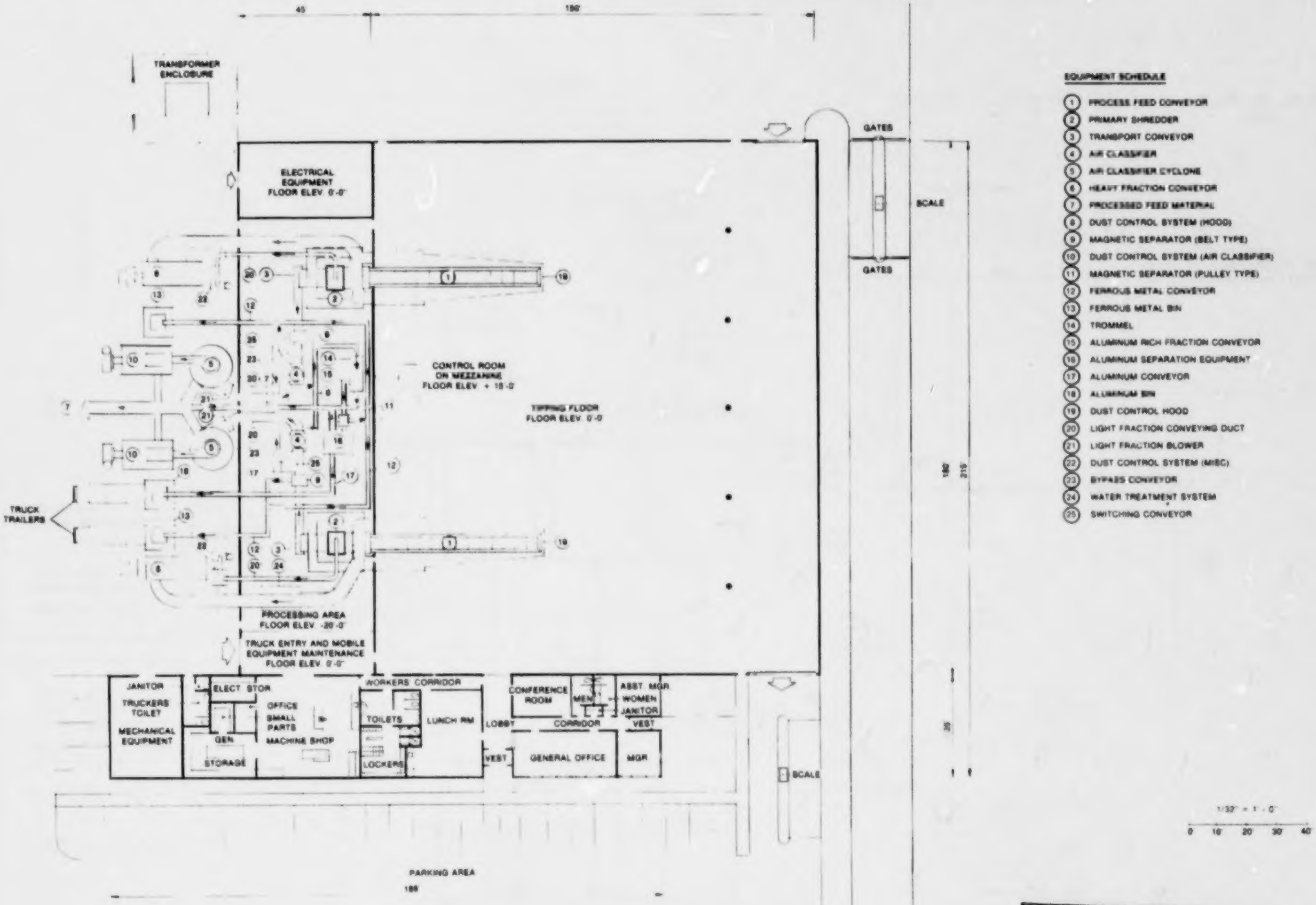

850'
720'
ROAD
ROAD
SLUDGE THICKENER
UNOX SYSTEM, TWO TRAINS FOUR STAGES
DAF
AIR COMPRESSOR AND POLYMER ADDITION FACILITY
SURGE TANK, PUROX CONDENSATE FROM PUROX DECANTING UNITS
NEUTRALIZATION AND NUTRIENT ADDITION FACILITY
DILUTION WATER FROM SEWAGE
BAR SCREEN GRIT CHAMBER AND FLOW CONTROL
MIXING TANK
CONTROL PANEL FILTER
CONTROL ROOM, LAB, AND PIPELINE COMPRESSOR
UNDERGROUND OIL STORAGE
ELECTRIC CONTROL PANEL REBOILER
EXCHANGER ABSORBER
GASOLINE PUMPS
FUTURE PLANT EXPANSION
TRANSFORMER ENCLOSURE
ELECTRICAL EQUIPMENT
PROCESSING AREA
SCALE
TIPPING FLOOR
MACHINE SHOP, LOCKERS TOILETS, LUNCHROOM, AND OFFICES
SCALE
PARKING AREA
FRONT-END PROCESSING PLANT
SCALE
0' 25' 50' 75' 100'
WASTE WATER TREATMENT
SECONDARY CLARIFIER
SLUDGE COLLECTING PIT
MAIN HOLE AND LIFT PUMP STATION
FLARING COMBUSTOR GAS COLLECTION MAIN
WASTE TO SYNGAS CONVERSION UNIT
CONDENSER
PRECIPITATOR
PRECIPITATOR
WASTE TO GAS CONVERTER
SLAG REMOVAL CONVEYOR
SLAG CONVEYOR
CONVERTOR FEED CONVEYOR
PROCESSED WASTE STORAGE
PROCESSED WASTE CONVEYOR
VALVE SKID ENCLOSURE
BLOWDOWN SILENCER
OXYGEN PLANT
FUTURE EXPANSION
COOLING TOWER
AIR SUCTION FILTER
NITROGEN TANK
AIR SURGE TANK
INSULATION TANK
LIQUID OXYGEN DRAIN TANK
COMPRESSOR HOUSE
COLUMN PACKAGE
TURBINE OIL CONSOLE
TURBINE DUCT
REVERSING H.X. PACKAGE
OXYGEN PUMP
COOLING TOWER
TL – 35,000 LIQUID OXYGEN STORAGE TANK
ACCESS ROAD

Figure 38. Site plan of solid waste to syngas conversion facility.


45
150'
TRANSFORMER ENCLOSURE
ELECTRICAL EQUIPMENT FLOOR ELEV 0'-0"
GATES
SCALE
GATES
CONTROL ROOM ON MEZZANINE FLOOR ELEV + 15'-0"
TIPPING FLOOR FLOOR ELEV 0'-0"
TRUCK TRAILERS
PROCESSING AREA FLOOR ELEV -20'-0"
TRUCK ENTRY AND MOBILE EQUIPMENT MAINTENANCE FLOOR ELEV 0'-0"
JANITOR
TRUCKERS TOILET
MECHANICAL EQUIPMENT
ELECT STOR
GEN
STORAGE
OFFICE SMALL PARTS
MACHINE SHOP
WORKERS CORRIDOR
TOILETS
LOCKERS
LUNCH RM
LOBBY
VEST
CONFERENCE ROOM
MEN
WOMEN
JANITOR
ASST MGR
CORRIDOR
VEST
GENERAL OFFICE
MGR
SCALE
180'
210'
35'
PARKING AREA
188
EQUIPMENT SCHEDULE
① PROCESS FEED CONVEYOR
② PRIMARY SHREDDER
③ TRANSPORT CONVEYOR
④ AIR CLASSIFIER
⑤ AIR CLASSIFIER CYCLONE
⑥ HEAVY FRACTION CONVEYOR
⑦ PROCESSED FEED MATERIAL
⑧ DUST CONTROL SYSTEM (HOOD)
⑨ MAGNETIC SEPARATOR (BELT TYPE)
⑩ DUST CONTROL SYSTEM (AIR CLASSIFIER)
⑪ MAGNETIC SEPARATOR (PULLEY TYPE)
⑫ FERROUS METAL CONVEYOR
⑬ FERROUS METAL BIN
⑭ TROMMEL
⑮ ALUMINUM RICH FRACTION CONVEYOR
⑯ ALUMINUM SEPARATION EQUIPMENT
⑰ ALUMINUM CONVEYOR
⑱ ALUMINUM BIN
⑲ DUST CONTROL HOOD
⑳ LIGHT FRACTION CONVEYING DUCT
㉑ LIGHT FRACTION BLOWER
㉒ DUST CONTROL SYSTEM (MISC)
㉓ BYPASS CONVEYOR
㉔ WATER TREATMENT SYSTEM
㉕ SWITCHING CONVEYOR
1/32" = 1'-0"
0 10 20 30 40

Reproduced from best available copy.

Figure 39. Front-end processing plant floor plan and equipment layout.

mobile equipment. An elevated control room is provided that directly oversees the tipping floor operations and monitors the processing area by closed circuit television.

The process area contain the waste processing equipment. This is a high bay area in which the floor level is 6.1 m (20 ft) below that of the tipping floor. The support services area is located in a one-story office and shop-type building attached to the main structure. Another area of the plant is outside adjacent to the processing area wall. This area contains the storage bins, truck loading facilities for the recovered metals and residue, exhaust fans, and filter baghouses for plant ventilation and dust control.

Plant Operation--

The control room provided above the tipping floor affords a full view of truck operations on the floor and the operation of the feed conveyor. The entire plant operation is monitored from the control room via remote START-STOP switches with appropriate interlocks for all processing equipment, a traffic signal system for directing incoming waste trucks, two-way radio to the tipping floor front-loaders, telephones, and a loud speaker intercom system to strategic points in the plant, including the weigh scales.

Organization of each processing line is in the manner of a continuous step-by-step sequence of operations with each piece of equipment sized to accommodate the volume of material coming to it from the operation immediately preceding. The flow is continuous from the start of processing to completion. The rate of processing is controlled by the rate waste is loaded onto the process feed conveyor from the tipping floor and by variation of the speed of the conveyor within the limits of equipment capacity. Flow of a load of solid waste can be traced in Figure 39, Floor Plan.

Process Equipment Trains--

The initial processing of the raw refuse is accomplished in two identical and independent trains of processing equipment, other than for a single aluminum recovery sub-system. Important processing equipment items, along with their performance requirements, are described below. The numbers in parentheses after the equipment name correspond to the equipment numbers in Figure 39. Sizes of equipment are given and were used in developing cost estimates.

Front-End Loaders are utilized for handling the received raw refuse on the tipping floor after it is deposited from the collection vehicles. They stack the refuse in piles and feed it to the shredder feed conveyors as required.

Each Process Feed Conveyor (1) consists of a two-section, heavy-duty, steel pan-type conveyor, 2 m (78 in.) in width. The first, or horizontal section, 24 m (80 ft) long, is mounted in a pit in the floor with the conveying surface 1.8 m (6 ft) below tipping floor level. To prevent damage from material dropped from the front-loaders, the conveyor pans must be formed from steel plate at least 10 mm (3/8 in.) thick and be suitably reinforced structurally. The pit has steel-plated sides sloping toward the conveyor at an angle of 30° from the vertical. This section discharges onto the second section, whose receiving end is below the first section and overlaps it slightly.

The Primary or Coarse Shredder (2) is a heavy-duty, horizontal, reversible hammermill rated for continuous duty at 54 Mg/h (60 TPH). This machine should be equipped with a heavy metal hood and conveyor entrance configuration to confine heavy material ballistically thrown by the rotating hammers. The grate openings are set for producing a shredded material that will have a maximum dimension of 20 cm (8 in.). The machine must be designed for ease in replacement of those parts subject to rapid wear, such as hammers, impact plates, grates and liners. Such a design should also incorporate easy-opening, hydraulically actuated doors to the grinding chamber.

The Magnetic Separator (9) used employs a suspended rubber belt having two magnets behind it, one near each end pulley. The material stream being processed is projected from its conveyor into the air under this magnet/belt unit. All the material passes through the first magnetic field with the ferrous material pulled up to the belt while the non-ferrous material falls by gravity toward a hopper feeding a conveyor. When the ferrous material passes between the two magnetic fields, it starts to fall from the belt and air currents separate paper, fabric, or plastics that have been trapped against the belt. The forward momentum of the ferrous materials carries them into the second magnetic field which pulls them back to the belt and from there they are conveyed to a ferrous metal hopper.

Each of two Air Classifiers (4,5,20,21) accomplishes air/density separation of the shredded material at a continuous rated capacity of 54 Mg/h (60 TPH). Equipment similar to the Chicago Supplementary Fuel Processing plant was used. Other systems are on the market and, since this is a developing technology, the final choice should be made based on system evaluation at time of detailed design. The system includes the air classifier proper, a light material conveying duct, an air supply blower, a material handling exhaust blower, and a cyclone type material separator. The light fraction drops from the bottom of the cyclone separator through an airlock onto the Processed Feed Material Conveyor (7). The heavy density material from the bottom of the air classifier is conveyed to the trommel preceding the aluminum separator. Installation of the air classifier is included only if it is economically feasible to recover aluminum.

The Trommel (14) is a conventional design rotating screen with two stages of separation, each with different screen openings. The trommel is sized to process 22.5 Mg/h (25 TPH) of 0.24 to 0.48 g/cm^3 (15-30 lbs/ft^3) density material. It also should have a dust shroud and hoppers to collect the separated material and feed the respective conveyors. The first stage screen passes material of less than 1.6 cm (5/8 in.) maximum dimension. The second stage separation screen passes up to 10.2 cm (4 in.) material, which is the aluminum-rich fraction, to the conveyor feeding the aluminum separation unit. The stream of material not passed through the screens is discharged from the trommel to the Processed Feed Conveyor (7).

The Magnetic Separator (11) is a standard drum-type separator that picks up the small amount of ferrous in the aluminum-rich stream that was not recovered by the first magnetic separator (9) and not lost in the first stage screen of the trommel (14). Ferrous material is deflected to a conveyor leading to ferrous bin.

The Aluminum Separation Unit (16) is an electromagnetic eddy-current-type machine that has been under development by several industrial firms. The system performance is designed to recover aluminum cans.

Aluminum and Ferrous Material Storage Bins (13 and 18) are elevated, bottom-dumping, truck-loading bins for holding the recovered metals that are separated in the plant and must be transported to a customer. There are two ferrous metal bins (13) associated with one shredder line, and designed for up to 4 Mg/h (4-1/2 TPH). A truck trailer is filled every 4-1/2 hrs to 5-1/2 hrs. The aluminum bin should be of 57 m^3 (2000 ft^3) capacity and will receive an 18 Mg (20 ton) load approximately every 3 working days.

There are three air-moving and Dust-Control Systems (8, 10, and 22) connected to each processing line. System (8) consists of a hood (19) suspended over the course shredder feed conveyor pit, a large filter baghouse, and an exhauster fan. The approximate air handling requirements are 35.4 m^3/s (75,000 CFM) for each shredder line. This system produces a sufficient number of air changes in the tipping floor area to maintain acceptable air quality and controls dust in the tipping floor area. By air removal at this point, air currents sweep the tipping floor and move dust generated from truck unloading toward the pit for ultimate removal. The filter baghouse collects the dust and prevents atmospheric contamination outside the building. A second major system (10) is for air classifier dust control. There are 31.9 m^3/s (67,500 CFM) of air flow from each air classifier cyclone (5) leading to a baghouse. It is desirable to keep occasional large particles out of the baghouse, and a secondary cyclone plus a dropout box must be provided ahead of the filter baghouse. A third and smaller system (22), handling approximately 7.1 m^3/s (15,000 CFM), is in the dust-laden air from the various dust hoods or other collection points in the process train.

Auxiliary Equipment--

In addition to the process equipment, certain items of support equipment or systems are important to the facility.

A Waste Water Treatment System (24) is provided for the tipping area and process area floors drainage system.

A house compressed-air supply of sufficient capacity and pressure is furnished for filter baghouse operation, instrumentation, air-operated controls, pneumatic tools, and other maintenance operations.

Truck scales, in the form of dual 50-ton capacity scales in the entrance roadway, are provided.

Heating, ventilating, and air conditioning is provided in necessary areas throughout the facility. Unless otherwise noted, all heat is by steam, generated with an oil-fired boiler located in the mechanical room. The tipping floor area is unheated because of the large quantity of ventilation air required to remove mobile equipment exhaust gases. Except in severe weather, the truck entrance and exit doors remain open during plant operations to allow major air inlet requirements to sweep across the tipping floor from the farthest corners to the hoods over the conveyor pits. An additional air inlet is provided by means of wall louvers. Steam pipes are imbedded in the floor for a distance of 3.6 m (12 ft) around the conveyor pits for use in cities with cold climates. The processing area has large quantities of air passing through because of air classifier requirements. The incoming air is heated by units mounted against the outside process room wall to temperatures at or above 4°C (40°F), unless the building code of the specific site chosen requires a higher minimum temperature. Wall-mounted unit space heaters are provided near the working floor levels for heating during maintenance periods.

Fuel storage is required for the 75 700 dm^3 (20,000 gallon) of oil needed each week for the heating system, during maximum winter load, plus some steam for the syngas plant wastewater treatment. A 120 000 dm^3 (30,000 gallon) underground storage facility is recommended. The front-loaders and residue trucks from the syngas plant require on-site diesel fuel storage plus a dispensing pump; a 20 000 dm^3 (5000 gallon) storage tank is recommended.

Fire protection must be provided in accordance with national and local codes. This requires complete sprinkler coverage in all areas. All areas can have a wet system except the tipping floor area, which requires a dry type because that room is subjected to freezing temperatures. The tipping floor must be provided with fire hoses to combat refuse fires anywhere on the floor. Other areas should be provided with wall-mounted hand extinguishers and hoses in accordance with established standards. Appropriate outdoor fire hydrants are also required.

Electrical systems require power to be received at a minimum of 4160 volts. The required capacity can be met by three 7500 kV-A substations for a total of 22,500 kV-A. Distribution of the 4160-volt circuits is from the outdoor line or substation to indoor 5-kV switchgear and from 5-kV starters to 4160-volt motors. Starters rated at 4 kV are indoor-type and arranged in line with the 5-kV switchgear. Load center-type unit substations are provided to transform 4160 V to 480/277 V. The 277/480 V feeders are extended from the motor control centers to distribution panels. Supplies to 120/208 V power and lighting panels are provided by dry-type transformers located at each panel and energized from the 480 V system.

A control system is provided for remote control of the process. Central panels are provided for each line for independent operation with interlocked controls for automatic sequential startup and shutdown of each major component of the line. In the event of shutdown or failure of a component, the rest of the line is programmed to shut down in proper sequence to avoid material jamming of machinery that cannot be restarted under load. The central control can also manually override the automatic programming. Local START-STOP controls are provided at each piece of equipment to permit emergency shutdown or facilitate maintenance operations.

Processed Feed Material Handling

A storage or surge bin is used for each gasifier to provide an even rate of feed 24 hours per day, 7 days per week from a processing plant that operates only 16 hours per day, 6 days per week. Storage capacity must equal 36 hours of consumption, or a minimum of 467 Mg (515 tons) per gasifier. An A-frame shaped bin to prevent bridging of the waste in storage and to permit access to the underside of the pile for the reclaim equipment permits material removal on a first-in, first-out basis. Each bin is 22.5 m (74 ft) wide at the base by 30.5 m (100 ft) long. Rotating augers move the material to a belt conveyor.

Purox Converter System

The Purox converter system is that developed as proprietary equipment by the Union Carbide Corporation. The three subsystems are designed and furnished by UCC as an integrated system to function in the required manner under warranties and performance guarantees. Operation is normally continuous. Monitoring is centralized in a control room located in a building that also houses a small chemistry laboratory and the product pipeline compressor.

Gasifier--

Each of these units consists of a feed material conveyor, a pyrolysis reactor, and gas cleanup equipment. Five conversion units of 317 Mg/d (350 TPD) capacity are provided. Four units operate continuously with one available as a standby. The reactors operate at high temperature and should be operated at design temperature as continuously as possible to minimize expansion/contraction cycling damage. In the event that feed supply is interrupted for a short period, or is furnished at a reduced rate, it is possible to turn down the conversion rate to as little as 25% of rated capacity and still keep the reactor at operating temperature and produce a satisfactory gas. However, the oxygen plant can be turned down to only 60% of design output. Beyond that requires venting excess oxygen. Use of two oxygen plants, each at half-size, allows for turn-down to 30% by shutting off one unit.

Oxygen Plant--

The source of oxygen for the Purox system will be an onsite cryogenic oxygen generating plant. The process involves the liquefaction of air followed by fractional distillation to separate its components. These plants are well known so that details of their operating characteristics need not be discussed here. Liquid oxygen can be transferred to storage facilities that will serve as a backup oxygen supply in the event of a plant outage. Facilities for transferring liquid oxygen from a transport vehicle are also included. For assistance in startup, the design is arranged such that liquid oxygen can be transferred from the storage tank into the cold box. Location of this plant should be upwind from any gas producing equipment with possible hydrocarbon or carbon oxides emissions. The cryogenic plant also supplies oxygen to the wastewater treatment system. Also, use is made of gaseous nitrogen production and liquid nitrogen storage for purging reactors and tankage. This nitrogen supply is critical for a plant safety program.

Wastewater Treatment Plant--

The wastewater treatment plant specified is Union Carbide's UNOX wastewater treatment system, which uses an oxygen activated sludge process for BOD reduction. The system consists of covered multistage biodigestion reactors in which oxygen is fed concurrently with the wastewater. The feed wastewater, recycled sludge, and oxygen are introduced into the first stage. Mixed liquor from the last reactor stage flows to a secondary clarifier that allows gravity separation of the biomass from the treated wastewater. The treated wastewater flows over a weir for discharge to a municipal wastewater treatment plant. The thickened biomass from the clarifier is recycled to the first stage of the reactor and excess biomass or sludge is pumped to a thickener prior to transport to a nearby municipal wastewater treatment plant for digestion.

Gas Compression and Drying

Because the syngas leaves the gasifier and cleanup system at approximately atmospheric pressure, a pumping system must be supplied to deliver the gas through a pipeline to a user. 446 kPa (50 psig) has been chosen as the lowest practical pressure that would deliver fuel gas at a high enough pressure for average purposes; if the gas were delivered to an adjacent chemical conversion or gas turbine-electric plant, a higher pressure would be required. Three electric-driven centrifugal compressors are used at 1865 kW (2,500 HP) each, operating in parallel. These machines are rated at 446 kPa (50 psig) discharge, pumping 635 kg (1,400 lb) per minute of a gas with a molecular weight of 25. Any two of these machines will carry the full load, thus providing sufficient redundancy to ensure full capacity. If the gas is to be piped any distance farther than to the immediately adjacent property, it must be dried to prevent condensation problems in the pipeline. A standard glycol gas drier is recommended. If an H_2S level of 400 ppm is not acceptable for a particular customer, a small sulfur removal unit can be additionally installed.

ESTIMATED CONSTRUCTION AND OPERATING COSTS

This section presents estimated capital and operation costs for the facilities for converting 1361 Mg/d (1,500 TPD) of solid waste to syngas. While the syngas produced can be used directly as a fuel in power plant boilers, it also can be chemically converted to other products as described in Appendix C. The cost estimates presented in this section are based on mid-1975 prices. The various cost elements are defined and cost sources are identified.

Capital Costs for Construction

Capital requirements for construction include land acquisition, site improvements, buildings, equipment, an inventory of working materials and spares, contingency reserve, engineering and construction management costs, interest during construction, startup costs, and a working capital fund. A summary of the estimated capital costs developed for the elements discussed below appears in Table 38.

Details of the construction costs are described below and are summarized in Table 39.

Taxes--

While the Contractor may need to pay a State sales tax, usually application can be made for a 100% refund. It is assumed that any local taxes or fees would be absorbed in the continency allowance. If the facility was owned by a municipality, no property tax liability would accrue. To the extent that unimproved property is removed from the tax rolls, there would be a minimal

TABLE 38. CAPITAL COST REQUIREMENTS FOR PUROX SYSTEM

Item	$ Million
Construction	53.75
Interest during construction	4.30
Startup costs	2.56
Working Capital	1.79
Total	62.40

TABLE 39. ESTIMATED CONSTRUCTION COST SUMMARY (1975 DOLLARS) FOR PUROX SYSTEM (1)

Item	Costs ($000)
Taxes (None Used)	------
Land Acquisition	468
Site improvement	880
Front-end processing plant	10,066
Processed feed material storage and handling facilities	3,476
UCC-supplied Purox equipment(2)	17,703
Purox equipment installation	10,675
Gas pumping and drying station	2,410
Subtotal	45,678
Contingencies @ 10%	4,567
Engineering and construction management @ 10% less 6% engineering on UCC-supplied Purox equipment	3,505
Total	53,750

(1) Front end, processed feed handling, and gas compression & drying unit are Parsons designs.

(2) Includes oxygen and waste water treatment units

loss in tax revenues to the local government. No taxes were included in construction costs shown but there would be a need to review each specific case.

Land Acquisition--

The land requirement is 87 010 m^2 (21.5 acres). At a cost of $0.50/$ft^2$, the cost of the site is $468,000.

Site Improvement--

Site improvement costs include such items as clearing and grubbing, rough grading, and construction of utility mains from the site to the supply mains. Paving, fencing, and landscaping are also included as site improvements. Site improvement costs are listed in Table 40. The amounts listed should be considered as reasonable allowances because the actual costs will be site-specific and cannot be accurately estimated at this time.

TABLE 40. SITE IMPROVEMENT COSTS FOR PUROX SYSTEM

Item	Cost ($000)
Clearing and grubbing	40
Utilities	240
Earthwork (excavation, backfill, and disposal)	270
Fine grading	40
Paving	200
Landscaping	40
Fencing	50
Total	880

Front-End Processing Plant--

Costs for this portion of the facility are summarized in Table 41. The cost estimates for the building are based on Parsons estimates for several similar facilities and are verified by one such facility designed by Parsons in Chicago and for which actual construction costs are known. Costs for this building include miscellaneous support equipment not itemized elsewhere, such as the house air system and fire protection system. The main process equipment and related costs are based on purchase prices of equipment procured on other projects, modified to reflect inflation escalation or updated quotations received directly from equipment vendors. Installation costs are also shown. These include only final electrical connection to the equipment components from a nearby junction box. The major electrical distribution is included in the building electrical cost listing. The bridge crane installation includes only setting the bridge on the rails because the rails and electrical are included in the building costs.

TABLE 41. FRONT-END PROCESSING PLANT FOR USE IN PUROX SYSTEM

Item	Cost ($000)
Building:	
Piling allowance	330
Foundations	861
Structural	1,188
Architectural	461
Mechanical (except HVAC)	1,306
Heating, ventilating, and air conditioning (not including dust control)	440
Electrical (including substation)	922
Subtotal	5,508
Process Equipment:	
Front-end loaders	208
Shredders	534
Conveyors	398
Air classifier systems	470
Magnetic separators	46
Trommel	85
Aluminum system conveyors	80
Aluminum separation unit	415
Material storage and truck loading bins (installed)	116
Ferrous and residue trailers and tractors	250
Pickup truck	5
Truck weighing scales (installed)	85

(continued)

TABLE 41 (continued)

Item	Cost ($000)
Process Equipment (continued)	
Dust control systems	1,140
Bridge crane (installed)	120
Subtotal	3,952
Equipment installation (not included elsewhere)	448
Spare parts and tools	158
Total	4,558
Total Plant Costs	10,066

Process Feed Material Handling and Storage--

The shredded refuse bins are simple A-frame structures with concrete foundations. The cost for the five units, including lighting and ventilation, is $2,125,000. The material receiving and delivering equipment for the storage bins is listed and costs are shown in Table 42 at a total cost of $1,351,000 installed in addition to the amount above. The total cost for the feed material handling and storage equipment is then $3,476,000. This cost is not listed in Table 41 as part of the Front-End Process Plant but is included in Table 39 as an item in total construction costs. The storage and material receiving and reclaim equipment design is unique to the Purox System in that there is a surge bin for each reactor. If another method of storage is desired, its costs can be substituted for the one presented herein.

UCC-Supplied Purox Equipment--

This item is the mid-1975 quoted price of $17,703,000 for the hardware supplied by Union Carbide Corporation as the basic Purox system equipment, listed in Table 39. This price includes the reactors, their feed and residue conveyors, the gas cleanup train, emergency flare, oxygen plant, and auxiliaries for waste water treatment. The general scope of supply for the Purox system (4 units plus one space) is listed below with the number of units in parenthesis for a 1361 Mg raw refuse per day (1,500 TPD) plant.

- Purox System 317 Mg/d (350 TPD) reactor (5)

    Converter feed conveyor (5)

    Feed conveyor refuse leveler (5)

    Refuse feeders (5)

TABLE 42. FEED MATERIAL HANDLING EQUIPMENT COST FOR USE BY PUROX SYSTEM

Item	Cost ($000)
Material Receiving Equipment	
Receiving conveyor: weather-shielded, -54-in. flat belt 2 required, installed	192
Distribution conveyor: 54-in. flat belt, 113 ft long 1 per bin installed	130
Traveling plow on distribution conveyor 1 per bin @ $5,200 installed	26
Inclined conveyor: weather-shielded, 48-in. cleated belt type with metal sides 2 required, 90 ft long, plut 15% installation	100
Automatic conveyor sequencing control	6
Conveyor wiring @ 15% of purchase cost	60
Total	514
Material Reclaim Equipment	
Bin unloader assemblies: Miller-Hofft 2 required per bin @ $54,000 installed	540
Bin discharge conveyor: 48-in. wide troughed belt conveyor 110 ft long 2 required per bin installed	202
Conveyor wiring @ 15% of purchase cost	95
Total Delivery Equipment	837
Total Feed Material Handling Equipment	1,351

Refuse converters (5)

Slag quench tank and conveyors (5)

Electrostatic precipitators (5)

Condensate pumps (10)

Condensers (5)

Solid-Liquid Separation System (5)

Combustors (3)

- Wastewater Treatment System (5.78 m^3/min. or 2.2 MGD)
    - Surface aerators, electric motors, gear boxes and skids, special valves
    - Purge blower
    - Instrumentation and controls
- Air Separation Plant (363 Mg/d or 400 TPD)
    - Interchanger
    - Liquid oxygen storage
    - Air compressor and driver
    - Aftercooler
    - Expander turbine
    - Oxygen vaporizer
    - Air surge tank
    - Blowdown silencer
    - Drain vaporizer
    - Thaw system
    - Liquid oxygen pumps (4)
    - Booster compressor
    - Circuit breaker panel
- Instrumentation
    - Local and remote control panels
    - Controllers, control valves, transmitters, and analyzers associated with supplied equipment
- Engineering Services
    - Design, specification, procurement, and checkout of supplied equipment and instrumentation

Installation of Purox Equipment--

The installation of the Purox equipment and related auxiliaries amounts to $10,675,000 and is shown as a separate item in Table 39. Parsons was unable to estimate this cost in the usual manner due to lack of sufficiently detailed data. The figure is based on Union Carbide Corporation estimates with some adjustment by Parsons, based on discussions with UCC personnel. Specific items that this cost must include are:

(1) Utilities, such as steam, cooling water, electric power, and instrument air

(2) Electrical substations and switchgear

(3) Buildings, control room, and laboratory

(4) Interconnecting piping, tubing, and wiring

(5) Wastewater treatment auxiliary equipment, such as reactor pumps, clarifiers, and sludge thickeners

(6) Installation of Union Carbide-supplied equipment

(7) Spare parts and tools

(8) Area lighting

(9) Lift pump and connecting trunks to local sewer system

Contingency--

A reasonable, but conservative, total estimate of construction cost includes an estimated reserve for contingencies. The higher the contingency factor, the lower the confidence level in the accuracy of the cost estimate. Ten percent has been chosen for this facility because the basis for the estimate has been fairly well established, except, perhaps, for the installation of the Purox equipment.

Engineering and Construction Management--

The costs of preparing construction plans and for management of the project during construction are estimated as 10% of the construction costs.

Interest During Construction--

With construction of the facility scheduled over a period of 2 years, debt service will accrue on funds expended over that period. Previous studies indicate that interest on total construction cost is generally paid for one-half of the construction period and is so shown in Table 38.

Startup Costs--

The production startup costs include breaking in a new facility and correcting construction deficiencies. An allowance has been made for the fact that the facility incorporates new technology that does not have the benefit of many years of operational experience. It is assumed that operating costs for the first year will be that for operation under design conditions. However, the production rate (and hence, income) will be 10% of rated capacity during the first quarter, increasing to 35% in the second quarter, 65% in the third quarter, and finally, 92% in the fourth quarter, for an overall first-year rate of 51%. Since the plant does not operate at full capacity, it is reasonable to take a credit against operating costs for production-rate-related costs. These include power, mobile equipment fuel, extra raw refuse hauling, water, and residue disposal, which are described in operating costs below. Startup costs are estimated at 49% (100-51) less 25% of the production rate-related costs for a total of $2.56 million, as shown in Table 38.

Working Capital--

Working capital listed in Table 38, like startup cost, is estimated as a percentage of annual operating costs. For this study, the equivalent of 3 months operating costs, or 25% of annual operating cost, shown in Table 43 is used.

Operating Costs

Operating costs are those repetitive costs that occur as a result of operating the facility, including such items as direct labor, maintenance services and supplies, utilities, fuel, and transport costs. The estimates are reported on an annual basis and summarized in Table 43.

TABLE 43. SUMMARY OF OPERATING COSTS FOR PUROX SYSTEM

Item	Annual Cost ($000)
Labor (not including UCC personnel)	$2,159
Power	2,307
Heating fuel and miscellaneous	200
Process equipment and building maintenance supplies	840
Mobile equipment, maintenance and replacement	92
Mobile equipment fuel	28
Water and sewer	250
Extra raw refuse hauling	56
Residue disposal	45
Insurance	289
Union Carbide management fee	750
Total	7,016

Direct Labor--

A detailed review of all probable job assignments related to the plant size, type, location and probable plant operating schedule provides a reasonable manhour estimate by payroll category for direct labor. The dollar amount is determined by applying local wage rates for the same or similar tasks, including adjustments for shift differentials and anticipated overtime. The wage rates were determined on the baiss of the U.S. Bureau of Labor Statistics area wage survey (Bulletin 1850-15). Modifications can be made for specific localities. Table 44 presents a chart of personnel by category, number required, hourly rate, and disposition by shift for the front-end processing plant. Table 45 presents the same information for the syngas plant.

Table 46 summarizes labor costs. Included is a 50% hourly surcharge to cover fringe benefits and miscellaneous overhead costs such as payroll and accounting. Administration management is covered in a special cost item discussed later. The estimated overtime allowance of 3,300 hr/yr will permit development of a 6-day week operating schedule.

Shown in Table 46 are 6 standby personnel to fill in for vacations, sick leave, and overtime shifts for front end operators as follows: 1 process operator, 1 heavy equipment operator, 1 electrician, 1 mechanic, and 2 laborers. These people are assumed to be in training for a higher labor grade and are assigned to cover various positions. Also, 5 standby personnel are added for the Purox plant operation to fill in for vacations, sick leave, and overtime shifts as follows: 1 reactor monitor, 1 maintenance helper, 1 water treatment plant monitor, and 2 laborers.

Because the Purox plant operates continuously, it is possible to develop a rotating shift schedule with an overtime allowance of 2,400 hr/yr. This is accomplished with 4 men assigned to each shift-day position, as indicated in Table 45. Annual labor cost for the complete facility is $2,159,000 as shown in Table 46.

Electric Power--

Electric power costs were calculated on the basis of a 25 mills/kWh rate. A value for the cost of electric power in specific areas can be substituted by ratio in the calculations shown below. A typical 12-month operating schedule was assumed with a connected load of 20,000 hp and an average operating demand at a rated capacity of 14,800 kW. This is a capacity with both the front end and Purox system operating. A weighted average was computed on an annual basis, resulting in the following:

$$EC_eSW_y = AC_e$$

Where

E = kWh/ton raw refuse = 179

C_e = Average cost per kWh consumed = \$0.025

EC_e = Average cost per ton raw refuse = \$4.47

TABLE 44. PERSONNEL REQUIRED FOR FRONT-END PROCESSING PLANT

Total	Position	Basic Pay $/hr	1st Shift	2nd Shift[a]	3rd Shift[b]	Total $/Position/hr
1	Superintendent	10.00	1	0	0	10.00
3	Shift Supervisor	8.90	1	1	1 (Mech.)	27.10
4	Process Operator	7.19	2	2	0	29.06
7	Heavy Equipment Operator	7.19	4	3	0	50.79
2	Equipment Monitor Front-End and Aluminum	6.35	1	1	0	12.91
1	Mobile Equipment Mechanic	7.19	0	0	1	7.40
3	Maintenance Mechanic	7.19	1	1	1	21.97
3	Maintenance Mechanic	7.19	1	1	1	21.97
1	Maintenance Welder	7.19	0	0	1	7.44
3	Maintenance Helper	6.38	1	1	1	19.54
3	Yardman	6.38	1	1	1	19.54
4	Laborer	5.80	2	1	1	23.60
1	Janitor	5.80	0	1	0	5.95
2	Records Clerk-Steno	5.00	2	0	0	10.00
38	Total		17	13	8	267.39

[a] 2nd Shift, add $0.15/hr.

[b] 3rd Maintenance Shift, add $0.25/hr.

TABLE 45. PERSONNEL REQUIRED FOR PUROX SYNGAS UNIT

Total	Position	Basic Pay $/hr	1st Shift	2nd Shift[a]	3rd Shift[b]	$/Position/hr
1	Superintendent	c	1	0	0	-
1	Plant Engineer	c	1	0	0	-
4	Shift Supervisor	c	1	1	1	-
8	Process Operator	c	2	2	2	-
4	Heavy Equipment Operator (Residue)	7.19	1	1	1	29.29
8	Reactor Monitor	6.55	2	2	2	53.46
4	Feed Material Monitor	6.38	1	1	1	26.05
4	Product Compressorman	7.19	1	1	1	29.29
4	Maintenance Mechanic	7.19	1	1	1	29.29
4	Electrician	7.19	1	1	1	29.29
4	Maintenance Helper	6.38	1	1	1	26.05
8	Laborer	5.80	2	2	2	47.46
1	Instrument Technician	7.50	1	0	0	7.50
4	Water Treatment Plant Monitor	6.38	1	1	1	26.05
4	Water Treatment Plant Operator	7.19	1	1	1	29.29
63	Total		18	15	15	333.02

[a] 2nd Shift, add $0.15/hr.

[b] 3rd Shift, add $0.25/hr.

[c] These positions are furnished as part of Union Carbide Corporation's management fee.

TABLE 46. SUMMARY OF LABOR COSTS FOR PUROX SYSTEM

	Annual Cost ($000)
Regular Operating Positions:	
Front-end processing plant - \$267.30 x 2,080 hr/yr	555
Syngas plant - \$333.02 x 2,080 hr/yr (not including UCC personnel)	693
Standby personnel - average rate, including shift differential: front-end plant = \$6.86 syngas plant = \$6.32	
Front-end plant - 6 men x \$6.86 x 2,080 hr/yr	86
Syngas plant - 5 men x \$6.32 x 2,080 hr/yr	66
Overhead and fringe benefits @ 50%	701
Overtime:	
Front-end plant - 3,300 hr x \$6.86 x 1.5 (Premium)	34
Syngas plant - 2,400 hr x \$6.32 x 1.5 (Premium)	23
Total	2,159

SW_y = Yearly solid waste processed = 515,500 tons

AC_e = Total annual power cost = \$2,307,000

Maintenance Supplies and Services (not including mobile equipment)--

Because a large maintenance staff is a part of the base payroll, this item need cover only parts and special services, and is estimated at 2-1/2% of purchase price of mechanical equipment and 1% of building costs. In addition, a special cost of \$0.14/ton of raw refuse processed is added for the rapid wearing parts of the shredders, such as the hammers, for an annual cost of \$72,000. The total for maintenance supplies is \$840,000.

Mobile Equipment Maintenance--

This item is calculated at 8% per year of the purchase price, or \$37,000. In addition, it is presumed that this equipment will have to be replaced every 7 years resulting in providing a sinking fund payment of \$55,000/yr. This fund is anticipated to earn compound interest at 6-1/2%, which credit was not used in this report.

Process Steam, Heating Fuel, and Miscellaneous--

Steam for heating and other miscellaneous needs requires 13,000 bbl/yr of fuel oil resulting in a cost of \$182,000/yr. Allowing \$18,000 for miscellaneous items, such as telephone and office supplies, the total is \$200,000/yr.

Mobile Equipment Fuel--

This requirement is calculated at approximately 60,000 gal, or \$25,000 for the front loaders and 4,000 gal, or \$2,100 for the truck fleet, plus \$1,000 for gasoline for the pickup truck.

Water and Sewer--

The estimate of \$250,000/yr is based on discussion with water and sanitation district offices. A convervative cost of \$0.20/m^3 (\$0.75/1,000 gal) plus 55% for sewer charge, was established. Water usage in the plant will probably run in the 2082 to 2271 m^3/d (550,000 to 600,000-gpd) range. A special arrangement will probably have to be made considering the nature and needs of the water treatment plant. The accuracy of this cost is not high because of the uncertainties in connections, piping, pumps, and charges.

Residue Disposal--

Approximately 81 648 Mg/y (90,000 TPY) of residual material from the processing plant will have to be disposed to landfill (or stored and marketed). This material has a density of approximately 1.28 g/cm^3 (80 lb/ft^3) for a total of 64 230 m^3/y (84,000 yd^3/yr). Since disposal cost is calculated on a volumetric basis, the cost per ton will be less than for raw refuse. An allowance of \$45,000/yr is made for this disposal. Vehicles and personnel for hauling are provided for elsewhere in the plant costs.

Extra Raw Refuse Hauling--

To keep this plant a full operation, there may be need to bring refuse from more distant areas, particularly in the winter. Allowance has been made at the rate of \$56,000.

Insurance--

Insurance premiums are normally set by negotiation after inspection of the specific facility by the underwriters. Representative premiums were established by discussions with several insurance companies. The rates employed on the capital items were 0.25% for the front-end processing and material handling facilities, and 0.6% on the gas producing and handling facilities. General personnel liability is figured at 1.5% of direct payroll. Insurance premiums amount to \$267,000 and \$22,000, respectively, for a total of \$289,000 anually.

UCC Management Fee--

The Union Carbide Corporation presently has a policy by which sales contracts on all Purox plants have a reserve clause that provides the right for UCC to negotiate a contract to provide operating management for the plant. This fee was determined to be \$750,000/yr by UCC for this size plant. Included in the fees are payroll and overhead costs for the plant superintendent, the plant engineer, the shift supervisors, and the process operators, all of whom are provided by UCC.

Other Purox Gas Utilization Systems

Construction and operating costs for converting Purox gas to methane, electric power, methanol, and ammonia are presented in Appendix C. Presented are costs including values developed above for the front-end and syngas production plus the syngas utilization or conversion plant.

ECONOMIC ANALYSIS FOR PRODUCING SYNGAS

For purposes of example and to provide a first order economic comparison of the alternative systems, the parameter used is a net cost per unit of product. This is calculated from unit amortization cost plus unit operating cost less unit revenues from drop charges, sale of steel, and aluminum. Actual costs at the time the plant is put in operation can be estimated by applying escalation factors on the various items shown in the previous section.

An analysis is shown below for the syngas product case. Material can be found for other product cases in Appendix C.

The basis for obtaining the net costs presented is:

- Municipal solid waste delivery averages 1361 Mg/d (1,500 TPD)
- On a yearly basis, an appropriate utilization factor is used for each system.
- Drop charges of 0, \$5.51, and \$11.02/Mg (0, \$5, and \$10/T) of raw refuse.
- Steel revenues of \$44/Mg (\$40/T) of steel.
- Aluminum revenues of \$331/Mg (\$300/T) of aluminum.
- Amortization at 8.5% for 20 years.
- All costs are in 1975 dollars.
- Equipment sizes in the front end are based on a process rate of 109 Mg/h (120 TPH) with an equal split between two process lines.

Information is given here to show a possible range of net costs for producing a fuel gas using the Purox pyrolysis system. A complete financial analysis for a given community can be performed taking into account specific costs and financing methods to be associated with the project. Costs for producing syngas are more accurate and detailed than for the products described in Appendix C because of design and construction experience on the front end, and costing experience for the Purox System in recent studies for communities. Calculation of the unit costs and net cost for syngas production using a \$11.02/Mg (\$10/T) drop charge case is given in some detail below as an example for one of the cases evaluated. The plant capital cost is \$62.40 million from Table 38, and annual operating cost is \$7,016,000 from Table 43. Steel recovery is 111 Mg/d (122 TPD) and aluminum is 5.4 Mg/d (6 TPD). The utilization factor is 0.92 and the product rate is 250 x 10^6 Nm^3 (9.31 x 10^9 SCF) per year, with the corresponding yearly delivery rate of raw refuse at 456 957 Mg (503,700 tons). The items of net unit cost* are:

$$(1)\quad \text{Amort. Cost} = \frac{(\$62.40 \times 10^6)(0.10567)}{9.31 \times 10^9 \times 370} \times 10^6 = \$1.91/10^6\ \text{Btu} \qquad (1.81)$$

$$(2)\quad \text{Operating Cost} = \frac{7{,}016{,}000 \times 10^6}{9.31 \times 10^9 \times 370} = \$2.04/10^6\ \text{Btu} \qquad (1.93)$$

$$(3)\quad \text{Steel Rev.} = \frac{122 \times 365 \times 0.92 \times 40 \times 10^6}{9.31 \times 10^9 \times 370} = \$0.48/10^6\ \text{Btu} \qquad (0.45)$$

$$(4)\quad \text{Aluminum Rev.} = \frac{6 \times 365 \times 0.92 \times 300 \times 10^6}{9.31 \times 10^9 \times 370} = \$0.17/10^6\ \text{Btu} \qquad (0.16)$$

$$(5)\quad \text{Drop Charge (\$10/T)} = \frac{10 \times 503{,}700 \times 10^6}{9.31 \times 10^9 \times 370} = \$1.46/10^6\ \text{Btu} \qquad (1.38)$$

Therefore, the net cost for the \$10/T drop charge case is:

$$\overset{(1)}{(1.91} + \overset{(2)}{2.04} - \overset{(3)}{0.48} - \overset{(4)}{0.17} - \overset{(5)}{1.46})/10^6\ \text{Btu} = \$1.84/10^6\ \text{Btu}\ (\$1.74/\text{GJ})$$

This corresponds to \$12.56/ton (\$13.85/Mg) raw refuse.

For a drop charge of \$5/ton (\$5.51/Mg), the net cost is \$2.53/10^6 Btu (\$2.40/GJ) or \$17.56/ton (\$19.36/Mg) raw refuse. With no drop charge, the net cost is \$3.30/10^6 Btu (\$3.13/GJ) or \$22.56/ton (\$24.87/Mg) raw refuse. The net cost can vary widely over the United States or in other areas of the world due to the different values of off-setting revenues from drop charges, steel, and aluminum. In some areas, glass may produce sufficient revenues to justify a recovery system. Drop charges for present methods of disposal have risen to over \$16.53/Mg (\$15/ton) in some areas. If a market value for steel, aluminum, and the final fuel product (in this case, syngas) is known, a drop charge to break even can be determined and compared to existing drop charges as part of the decision-making process a community uses for selection of the best means of solid waste management.

If the calculation above is extended to a special case where the gas is sold at the battery limits for \$2.50/10^6 Btu (\$2.37/GJ) (equivalent to about \$15/barrel oil), the drop charge required would be about \$5/ton (\$5.51/Mg) refuse. This is attractive in almost any part of the U.S.

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*Calculations are shown in English units as an aid to understanding the parameters involved; the SI units following in parenthesis are in terms of \$/GJ.

ENVIRONMENTAL ASSESSMENT

Aqueous Effluents

Cooling tower water requirements are satisfied with city water. The relatively clean blowdown stream from the cooling water system consists of 3.3 dm^3/s (53 gpm) enriched in dissolved solids due to the concentration of original salts and the additional presence of corrosion inhibitors such as polyphosphates or organics. Total dissolved solids are estimated at 1200 mg/dm^3, with corrosion inhibitors contributing 50 mg/dm^3 to this value. The BOD of the blowdown stream is negligible. This water will be used for ash-quenching makeup water and waste water dilution. An additional minor blowdown stream, estimated at 0.2 dm^3/s (3 gpm), originates from the steam system (oil-fired steam generator) used for heating purposes; this stream has characteristics similar to the ones of the cooling water blowdown, and can be similarly disposed of. A small amount of city water, 0.6 to 1.3 dm^3/s, or 10-20 gpm, is used for cooling, with no contamination occuring during the process.

The heavily polluted aqueous waste stream generated from wet scrubbing of the pyrolysis gases, consisting of pyrolysis condensates plus water from drying the refuse feed, has a flow rate of 4.4 dm^3/s (70 gpm) and a BOD_5 of 50,000 ppm due to the presence of water-soluble organics such as alcohols, organic acids, and aldehydes. Table 47 presents measured results of the organic fraction in the condensate effluent to be treated. The BOD load is too high for a conventional activated sludge system, but could be handled by pretreating using oxygen in place of air, as in the Union Carbide Unox process. Dilution of this effluent will be required and is achieved by mixing the 4.4 dm^3/s (70 gpm) effluent stream with 92 dm^3/s (1,460 gpm) of sewage upstream of the

TABLE 47. CHARACTERISTICS* OF PUROX SYSTEM CONDENSATE EFFLUENT

Organic Compound	Max. Wt. % in effluent
Methanol	1.1
Ethanol	0.5
Acetone	0.5
Methyl ethyl ketone	0.1
Acetic acid	0.8
Propionic acid	0.4
Butyric acid	0.1
Furfural	0.5
Phenol	0.1
Benzene	0.06
Other	0.38
	4.54

* COD max 77,000 mg/dm^3; BOD max 52,000 mg/dm^3; pH min. 3.7; air stripping drops COD to 55,000 and BOD to 35,000

oxygen-activated sludge treatment. Other alternatives could be considered, such as the high-pressure oxidation process, using high-pressure air (11 030 kPa or 1,600 psi) at 150 to 315°C (300 to 600°F), or the activated carbon process. The wet oxidation process could reduce the BOD load to 400 ppm, and the carbon process to even lower values, but pilot plant tests would be required before drawing definite conclusions concerning effectiveness and costs. The concentration of organics is high enough (4.5%) that other chemical or physical procedures not usually considered in wastewater treatment could be attempted; examples are reduced pressure distillation, adsorption on nonionic resins, molecular sieves, or liquid-liquid extraction.

Gaseous Effluents

Table 36 shows contaminants measured by UCC at South Charleston in the Purox gas. Gaseous effluent streams are also generated in other sections of the syngas plant. The front end of the plant generates varying amounts of dust-laden air that is collected from covered conveyor belts and dusthoods and led to cyclones and baghouses at an estimated flow rate of 80.7 Nm^3/s (180,000 SCFM). These remove approximately 4.5 Mg/d (5 TPD) of dust particles from the air streams and release air to the environment that contains dust amounts well below applicable particulate standards. The light-fraction material from the air classifier used in the aluminum recovery process is separated from the air prior to storage in the surge bin by a de-entraining cyclone. Air from the cyclones, estimated at 60.3 Nm^3/s (135,000 SCFM), is conveyed through a baghouse prior to venting to the environment. The dust collected at 4.5 Mg/d (5 TPD) is added to the surge bin as part of the pyrolysis feed.

Air cooling of the water circulating in the cooling tower produces a drift corresponding to 0.1% of the cooling water loading. The total amount of cooling water for both the oxygen plant and the Purox system is 852 dm^3/s (13,500 gpm). Therefore, the drift consists of 51 dm^3/min. (13.5 gpm) with 61 g/min. (915 grains/min.) of particulates, a negligible amount, being released to the atmosphere on evaporation of the water in the droplets.

The oxygen plant separates 1450 Mg/d (1,600 TPD) of air into 290 Mg/d (320 TPD) of oxygen used in the Purox reactor, and 1160 Mg/d (1,280 TPD) of nitrogen, which is vented to the atmosphere. A portion of the nitrogen stream could be utilized in synthetic processes such as the generation of ammonia or as inert gas.

The oil-fired steam generator used for heating during the cold season and for supplying steam to the wastewater system consumes 114 to 500 kg/h (250 to 1,100 lb/hr) of No. 2 fuel oil. According to EPA-supplied emission factors, the maximum air emissions per hour are 1 kg (2.3 lb) of particulates, 5.7 kg (12.6 lb) of sulfur dioxide, 0.3 kg (0.6 lb) of carbon monoxide, 0.2 kg (0.5 lb) of hydrocarbons, and 4 kg (8.8 lb) of nitrogen oxides.

If the syngas produced is conveyed to a power plant by pipeline, moisture removal to an acceptable dewpoint is required. This is carried out in an air cooler and a glycol absorber. Glycol picks up some hydrogen sulfide (approximately 100 ppm out of a total of 500 ppm) from the syngas, together with the moisture; on regeneration of the glycol in a reboiler stripper, the hydrogen sulfide would be released to the air with the water, an unacceptable procedure. The regeneration effluent is therefore passed through a small combustor, which converts hydrogen sulfide to sulfur dioxide, and released 454 kg/h (1,000 lb/hr) of water and 6.4 kg (14 lb/hr) of sulfur dioxide to the air.

The syngas produced by the facility may have to be vented to the air in case of emergency. This would occur through a flare combustor that oxidizes all components to carbon dioxide and water (plus a small amount of sulfur dioxide) prior to release to the atmosphere. The flare is enclosed and not visible from the outside.

Solid Wastes

The 227 Mg/d (250 TPD) residue generated by the Purox process is an inert, glassy aggregate similar to blast furnace slag. This material is suitable for many applications such as road building and construction material. It can be landfilled if suitable markets do not develop.

Noise

Noise control is an integral part of the layout and design of the plant. Special attention during equipment design and engineering layout will be given to the air compressor (oxygen plant), gasifier (Purox system), fans, fixed heaters, and the shredder.

Odor

No noxious odors are expected from a properly run refuse processing plant. No odors are produced from the pyrolysis reactors or oxygen plant.

Traffic

Traffic generation of a syngas plant is essentially that due to the incoming and outgoing wastes. Approximately 280 refuse collection trucks per day will arrive and depart the plant Monday through Friday, and about 140 trucks will be handled on Saturday. Residue must be hauled from the plant to the nearby landfill at a rate of one truckload every 2 hours; traffic impact is expected from this around-the-clock operation if in an industrial or landfill area.

Visual

No commercial syngas plant exists on which to base an evaluation of the visual impact of such a facility. However, a probable syngas plant layout and artist's perspective are included in this report. The plant can be described as visually characteristic of industrial type plants. The exposed pyrolysis reactors and the liquid oxygen plant are to be especially noted in this respect. While the plant shown is generally devoid of visually attractive architecture and landscaping, it is doubtful that even careful attention to these disciplines would allow such a facility to visually blend with other than industrial areas. If near a residential area, much of the plant can be enclosed attractively and safely with, of course, additional expense.

Probable Environmental Effects of Proposed Projects

Air Quality--

A syngas plant project will not significantly affect existing air quality levels. Emissions from the plant consist of vented, dust-free air, stack gas from an oil-fired steam generator used for heating during the cold season, and some sulfur dioxide from the gas dryer, if such dryer is needed. The total difference in vehicle miles compared to an existing refuse system cannot be determined until specific plant and disposal sites are selected. Emissions from the plant have been estimated in Mg/y (tons per year) as 2.7 (3) for parculates, 61.7 (68) for sulfur oxides, 8.2 (9) for carbon monoxide, 7.3 (8) for hydrocarbons and 21.8 (24) for nitrogen oxides. These are not items in the syngas which is passed through a pipe to a customer.

It is of interest to determine emissions that would occur if the syngas were burned in a utility type furnace. Based on data furnished by UCC and generic data for boilers using gaseous fuel, the following Parsons estimates were computed in Mg/y (tons per year): particulates, 32.6 (36); SO_2 285 (314); NO_x, 154 (170); hydrocarbons 10.9 (12); and CO nil. Removing H_2S from the syngas by well tested techniques can reduce the SO_2 to less than 4.5 Mg/y (5 TPY) and with the use of staged combustion the NO_x can be reduced considerably.

Water Quality--

Water quality will not be affected by a syngas project. A relatively low volume of wastewater will be generated and this will be discharged to existing sewage treatment facilities. Syngas plant effluent will be pretreated before release to the sewage system to meet criteria established by the sewage plant operators.

Solid Waste Disposal--

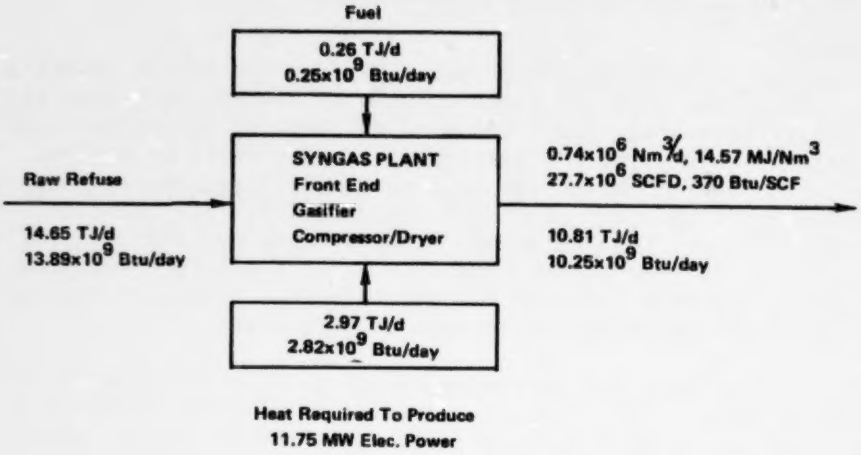
A Purox syngas project will significantly reduce the volume of solid waste requiring disposal in a landfill. This will increase the lifetime of the existing landfills. Additionally, the landfill residue will be less likely to leach into percolating waters and ultimately into the groundwater.

Land Use--

The increased lifetime of existing landfills will reduce the amount of new lands that must be set aside for landfills. A gas line would have to be constructed to link a syngas plant with any steam plant. Construction of this line could affect numerous land uses along the route. An analysis of the environmental effects of the pipeline must be addressed in the pipeline route selection study.

ENERGY BALANCE

Presented in this section are the energies associated with the raw refuse, fuel and electric power required for operation, and the products. The residue is inert and does not account for any energy. For the syngas plant, the energy balance is given as follows:


Fuel
0.26 TJ/d
0.25x10^9 Btu/day
Raw Refuse
14.65 TJ/d
13.89x10^9 Btu/day
SYNGAS PLANT
Front End
Gasifier
Compressor/Dryer
0.74x10^6 Nm^3/d, 14.57 MJ/Nm^3
27.7x10^6 SCFD, 370 Btu/SCF
10.81 TJ/d
10.25x10^9 Btu/day
2.97 TJ/d
2.82x10^9 Btu/day
Heat Required To Produce
11.75 MW Elec. Power

The conversion efficiency is

$$\frac{10.81}{14.65} \text{ or } \frac{10.25}{13.89} = 73.8\%$$

and the net thermal efficiency (English units) is

$$\frac{10.25 - (2.82 + 0.25)}{13.89} = 51.7\%$$

DETAILED SUMMARY OF PRODUCTION AND COSTS FOR PUROX SYNGAS

Summary of Product Rates

The rates of MSW delivery and processing are as follows:

Process	Type of Operation	Daily Weight MSW Processed
Delivery or Receiving	8 hours, 6 days	1588 Mg (1,750 tons)
Front end Processing	16 hours, 6 days	1588 Mg (1,750 tons)
Purox Gasifier	24 hours, 7 days	1361 Mg (1,500 tons) MSW equivalent 1239 Mg (1,366 tons) Shredded Feed

The daily and yearly product rates of various items are shown in Table 48. Daily rates are for 24 hours/day operation and the yearly rates take into account a utilization factor of 0.92 based on scheduled and estimated unscheduled shutdowns.

TABLE 48. SUMMARY OF PLANT PRODUCTION FOR SYNGAS AS FUEL
1361 Mg/d (1,500 TPD) PLANT

Product Item	Quantity
Raw refuse processed per day, Mg (ton)	1588 (1,750)
Raw refuse processed per week, Mg (ton)	9 526 (10,500)
Raw refuse processed per year, Mg (ton)	457 000 (503,700)
Ferrous product recovered per day, Mg (ton)	111 (122)
Ferrous product recovered per year, Mg (ton)	37 170 (40,970)
Aluminum product recovered per day, Mg (ton)	5.4 (6.0)
Aluminum product recovered per year, Mg (ton)	1 823 (2,010)
Residue to landfill per day, Mg (ton)	222 (245)
Residue to landfill per year, Mg (ton)	74 700 (82,300)
Product gas volume per day, 10^3 Nm^3 (10^6 SCF)	742 (27.71)
Product gas volume per year, 10^6 Nm^3 (10^6 SCF)	249 (9,310)
Gas energy per day, TJ (10^9 Btu)	10.81 (10.25)
Gas energy per year, TJ (10^{12} Btu)	3633 (3.444)

Utilization factor of 0.92 for yearly operation values.

Calculation of Net (Unit) Costs

Net costs (or unit costs) have been calculated for syngas based on the previously described revenue assumptions. A simplified equation characterizing the calculations is:

$$\text{Net Cost } \frac{\$}{\text{Trr}} = \frac{C \times F}{SWy} + \frac{OM}{SWy} - D - R_s - R_a$$

Where

C = Capital cost = construction cost + interest during construction + startup costs + working capital, $

F = Amortization factor = $\frac{i}{1 - (1 + i) -n}$

i = Interest rate per year

n = Number of year for amortization

SWy = Solid waste delivered, tons/y

OM = Operating and maintenance cost = labor + power + maintenance + production materials + water and sewage costs.

D = Drop charge, \$/ton raw refuse

R_s = Steel revenues, \$/ton steel x $\frac{\text{TPD steel}}{\text{TPD raw refuse}}$

R_a = Aluminum revenues, \$/ton aluminum x $\frac{\text{TPD aluminum}}{\text{TPD raw refuse}}$

Trr = Tons raw refuse

The net cost in other units can be similarly derived.

A community can make appropriate changes in each item given in the above formula to fit other specific cases and determine the corresponding unit costs. Also, escalation of costs and revenues can be introduced for each item and an actual net cost determined for design, installation, and operation on a real time basis. A period of 4 years is appropriate for accomplishing preliminary engineering, financing, detailed engineering, construction, and startup.

Because operating costs and revenues will change over the life-time of the plant, it is recommended that a cash-flow analysis be used to provide a more accurate picture of eventual net costs (or revenues). The actual market value for syngas can vary greatly depending on competitive fuel prices, environmental requirements, governmental incentives, etc. For these latter reasons, a cash flow analysis may be difficult to make. The more optimistic view is that market prices for fuels and materials will rise similarly to construction costs.

Costs and Economics as a Function of Syngas Fuel Plant Size

Costs are estimated for three plant sizes based on multiples of Purox gasifier modules, each with a 317 Mg/d (350 TPD) capacity. Sizes chosen were 635 Mg/d (700 TPD) (2 modules), 1361 Mg/d (1500 TPD) (4 modules), and 1905 Mg/d (2100 TPD) (6 modules). The base case previously evaluated was for a 1361 Mg/d (1500 TPD) plant using 4 modules plus one spare. Union Carbide requested that a spare be available in the two larger size ranges. Costs were therefore estimated for 4 or 5 modules at the 1500 TPD capacity and 6 or 7 modules at the 2100 TPD capacity.

The construction costs are evaluated for the different capacities based on the more detailed values determined previously and summarized in Table 49. For Purox equipment, costs vary somewhat linearly because of modularization. Other equipment costs vary with the 0.8 power of plant capactiy. For the operating costs summarized in Table 50, total cost of labor varies only slightly with capacity because of the minimum number of personnel to manage and operate the plant. Production-related supplies or utilities vary somewhat linearly with capacity. A Union Carbide management fee is shown as explained previously.

An estimation was made for either using or not using a spare for the two larger plant size cases. Because of the increased reliability of having a spare, a utilization factor of 0.92 (48 out of 52 weeks) was used and 0.85

TABLE 49. CONSTRUCTION COSTS TO PRODUCE SYNGAS AS A FUNCTION OF PLANT SIZE ($000) 1975

	Plant Size				
	635 Mg/d (700 TPD)	1361 Mg/d (1,500 TPD)		1905 Mg/d (2,100 TPD)	
No. of Modules	2	4	5 one spare	6	7 one spare
Land	269	468	468	612	612
Site Improvement	505	880	880	1,152	1,152
Front End Processing Plant	5,003	10,066	10,066	13,920	13,920
Process Feed Storage & Handling	1,390	2,781	3,476	4,171	4,866
UCC-Supplied PUROX Equipment	9,460	14,160	17,703	21,240	24,780
PUROX Equipment Installation	5,130	8,929	10,675	12,350	14,770
Gas Pumping & Drying Section	1,384	2,410	2,410	3,333	3,333
SUBTOTAL	22,141	39,694	45,678	56,778	63,433
Contingency @ 10%	2,214	3,969	4,567	5,678	6,343
Engineering and Construction Management @ 10%, less 6% UCC-Supplied Equipment	1,646	3,120	3,505	4,403	4,856
TOTAL	26,001	46,783	53,750	66,859	74,632

TABLE 50. ANNUAL OPERATING COSTS ($000) 1976 FOR SYNGAS PLANT

	Plant Size				
	635 mg/d (700 TPD)	1360 Mg/d (1,500 TPD)		1905 Mg/d (2,100 TPD)	
No. of Modules	2	4	5 one spare	6	7 one spare
Utilization Factor	0.80	0.85	0.92	0.85	0.92
Labor	1,880	2,159	2,159	2,440	2,440
Power	1,200	2,307	2,307	3,450	3.450
Process Equipment and Building Supplies	420	840	840	1,260	1,260
Heating Fuel and Miscellaneous	150	200	200	280	280
Mobile Equipment and Replacements	60	92	92	130	130
Mobile Equipment Fuel	15	28	28	42	42
Water and Sewer	125	250	250	375	375
Extra Refuse Hauling	20	56	56	75	75
Residue Disposal	23	45	45	68	68
Insurance	121	215	289	302	340
Union Carbide Management Fee	500	750	750	850	850
TOTAL	4,514	6,942	7,016	9,372	9,410

for no spare. For the 635 Mg (700 ton) case with two modules only and no spare, the reliability is considered less, at 0.80.

Figure 40 shows the variations of net unit cost, based on the heating value of the fuel gas, as a function of plant size with and without a spare. It should be particularly noted that using a spare costs less in the higher capacity range because of the increased utilization factor. In other words the estimated increased reliability of production of fuel gas for sale over a one year period is sufficient to justify the expense of a spare. Operating experience will determine whether or not a spare is justified.

Table 51 shows the capital required to build and bring the plant to full operation.

The economics of plant operation are calculated on the same basis as previously and results are summarized in Table 52 A&B. Amortization of capital requirements is based on 8-1/2% interest over 20 years. Credit is taken for aluminum and steel recovered at $330 and $44 per Mg ($300 and $40 per ton) respectively. These credits can be easily interchanged with other values and new net costs calculated in Table 52 A&B.

TABLE 51. CAPITAL COSTS ($000) FOR SYNGAS PLANT

	Plant Size				
	635 Mg/d (700 TPD)	1360 Mg/d (1,500 TPD)		1905 Mg/d (2,100 TPD)	
No. of Modules	2	4	5 one spare	6	7 one spare
Construction	26,000	46,780	53,750	66,860	74,630
Interest During Construction	2,080	3,740	4,300	5,350	5,970
Startup Costs	1,750	2,530	2,560	3,280	3,270
Working Capital	1,130	1,740	1,790	2,340	2,350
TOTAL	30,960	54,790	62,400	77,800	86,220

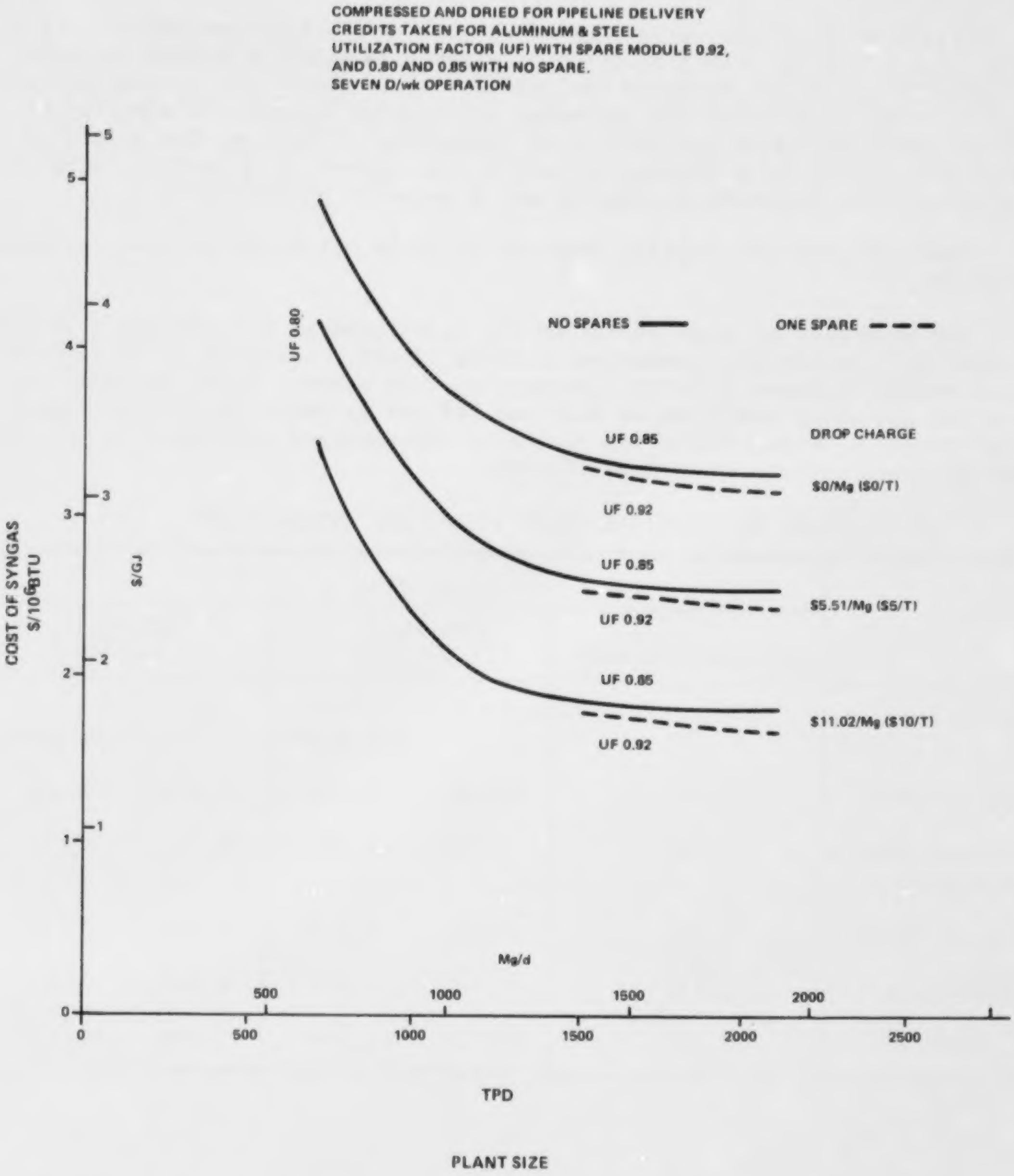


Figure 40. Cost of producing syngas.

TABLE 52A. SUMMARY OF NET UNIT COST TO PRODUCE PUROX SYNGAS AS A FUNCTION OF PLANT SIZE (SI UNITS)

Item		Plant Size				
		635 Mg/d	1361 Mg/d		1905 Mg/d	
No. of Modules		2	4	5 one spare	6	7 one spare
Capital ($000)		30,960	54,790	62,400	77,800	86,220
Amortization ($000/y) 8-1/2%, 20 years		3,272	5,790	6,594	8,221	9,111
O & M ($000/y)		4,514	6,952	7,016	9,372	9,410
Total Cost of operation ($000/y)		7,786	12,742	13,610	17,593	18,521
Utilization Factor		0.80	0.85	0.92	0.85	0.92
Refuse Feed (Gg/y)		185.43	422.21	456.95	591.04	641.84
Product Gas (10^6 Nm^3/y)		101.16	230.31	249.41	322.44	349.88
Product Gas (GJ/y)		1 474	3 356	3 633	4 698	5 102
Aluminum & Steel Credits (10^6\$/y)		946	2,147	2,243	3,003	3,261
Net	Drop Charge, $/Mg					
Cost,	0	36.88	25.10	24.60	23.70	23.78
$/Mg	5.51	31.37	19.60	19.09	19.17	18.27
	11.02	25.86	14.08	13.61	13.65	12.75
Net	Drop Charge, $/Mg					
Cost,	0	4.64	3.16	3.13	3.11	3.00
$/GJ	5.51	3.95	2.46	2.39	2.42	2.29
	11.02	3.26	1.76	1.74	2.04	1.60

TABLE 52B. SUMMARY OF NET UNIT COST TO PRODUCE PUROX SYNGAS AS A FUNCTION OF PLANT (SIZE (ENGLISH UNITS)

Item		Plant Size				
		700 TPD	1,500 TPD		2,100 TPD	
No. of Modules		2	4	5 one spare	6	7 one spare
Capital ($000)		30,960	54,790	62,400	77,800	86,220
Amortization ($000/y) 8-1/2%, 20 years		3,272	5,790	6,594	8,221	9,111
O & M ($000/y)		4,514	6,952	7,016	9,372	9,410
Total Cost of operation ($000/y)		7,786	12,742	13,610	17,593	18,521
Utilization Factor		0.80	0.85	0.92	0.85	0.92
Refuse Feed (TPY)		204,400	465,400	503,700	651,500	707,500
Product Gas (10^6 SCFY)		3,776	8,597	9,310	12,036	13,060
Product Gas (10^6 Btu/y)		1,397,000	3,181,000	3,444,000	4,453,000	4,836,000
Aluminum & Steel Credits (10^3\$/y)		946	2,147	2,243	3,003	3.261
Net	Drop Charge, $/T					
Cost,	0	33.46	22.77	22.56	22.39	21.57
$/T	5	28.46	17.77	17.56	17.39	16.57
	10	23.46	12.77	12.56	12.39	11.57
Net	Drop Charge, $/T					
Cost,	0	4.90	3.33	3.30	3.28	3.16
\$/10^6 Btu	5	4.17	2.60	2.53	2.55	2.42
	10	3.44	1.86	1.84	1.82	1.69

SECTION 9

OCCIDENTAL RESEARCH CORPORATION FLASH PYROLYSIS SYSTEM

INTRODUCTION AND SUMMARY

Unique among the fully researched waste-to-energy systems in that a liquid fuel is directly produced, the flash pyrolysis process of the Occidental Research Corporation (formerly Garrett Research and Development Company) is now entering the stage of development that will establish the technological, economic, and environmental feasibility for potential commercialization. The demonstration plant features a high degree of materials recovery. Its chemical conversion system is characterized by an inert hot char heat exchange system that prevents any oxidation of the original waste or the pyrolytic produced fuel.

In 1968, as an outgrowth of research on the conversion of coal to a low-sulfur fuel oil, Occidental Research Corporation (ORC) began studies on means to convert the organic portion of municipal refuse to a usable liquid fuel as well as to recover metals and glass from it. The decision was made in the early stages of development that the materials should be separated in a rather high degree of purity so that markets for them could be assured. This objective has apparently been met through the several R & D programs.

Fundamentals of the conversion process were established with laboratory equipment capable of processing 1.4 kg/h (3 lb/hr). Waste feed, in addition to municipal refuse, included bark, rice hulls, sewage sludge, animal manure, and rubber. This work was scaled up to a 3.6 Mg/d (4 TPD) pilot plant where the critical process variables were investigated, materials handling problems resolved, and sufficient product produced to establish its properties, including those as a fuel in burner test equipment. Information was obtained to serve as the basis for the design of a 181 Mg/d (200 TPD) plant at El Cajon (near San Diego), California, now undergoing start-up tests. While the description presented here is of the new facility, yields and product properties are necessarily based on work accomplished during the earlier R & D phases.

The most complete published descriptions of the Occidental process are those cited in References 16 and 17, while References 18 and 19 present other aspects of the work.

CONCLUSIONS

- Liquid fuels offer significant advantages. Large weights of liquids can be stored in relatively inexpensive tankage in contrast to gas, where production (or transport) must be more or less adjusted to usage. Where liquid fuels have low sulfur and ash contents, they can be utilized in existing gas/oil furnaces having minimum cost pollution control systems. The Western States in particular have few coal-fueled boilers and a waste-derived liquid fuel is far more attractive than a solid RDF. No other waste-to-energy process for yielding a fuel oil is at all as thoroughly investigated as is the ORC one and those organizations having narrowed their options to gaseous or liquid fuels should give detailed consideration to it. Cost analysis should be made on the basis of locally acceptable fuel oil sales prices rather than national average energy costs.

- The front end materials processing and recovery systems of the demonstration plant are among the most advanced known. The performance of such equipment should be reviewed and analyzed to determine its applicability to other waste-to-energy processes to increase overall plant revenues.

- Only limited characterization of the pyrolysis oil has been accomplished. Statistical variation of input waste composition should be made and effects on the oil measured. Properties to be examined should include chemical composition, density, viscosity and pour points, stability, corrositivity, and the usual combustion tests applied to new fuels.

- Fuel value remains in the char, but the high ash content renders it of marginal value at the present time. Uses for this material should be further explored.

- Waste feedstocks other than MSW should be used at El Cajon once sufficient information is obtained in the refuse testing program.

- The chemistry of the process leads to a conversion efficiency lower than most waste-to-energy systems. In no way should this efficiency be viewed as negating the value of the process. To obtain a barrel of oil from a ton of waste is of great importance to the nation's energy program and the scheme should be so judged.

- The demonstration plant can serve as an excellent research tool to determine product characteristics as functions of waste particle size, reactor temperature, and residence time. The original small-scale Occidental research demonstrated that a range of gaseous and liquid molecular species could result and advantage should now be taken of the large unit to learn what fuels can be synthesized.

PROCESS DESCRIPTION

The prime concern of this report is waste-to-energy conversion. The materials recovery portion of the Occidental process, however, cannot be isolated from the pyrolysis sub-systems of the overall scheme. The equipment is energy consuming, but the revenues potentially generated from sales of glass, steel, and aluminum have significant effects on plant economics and thus the required selling price of the pyrolytic fuel oil. To consider only the energy-producing steps would lead to erroneous conclusions as to the cost effectiveness of the process.

Figure 41 shows the process schematic of the Occidental resource recovery system, basically consisting of a "front end" physical processing and materials separation section and a pyrolysis/purification section. The functions and operating characteristics of the equipment within these two sections are discussed separately below.

Raw refuse composition serving as the basis for design was established both from experience in pilot plant tests and examination of available survey information. The values used by ORC in the following table are sufficiently close to those in the EPA "Third Report to Congress" that no attempt has been made to adjust them.

		Daily Input	
Component	Amount, Wt-%	Mg	Tons
Organics (dry)	54.4	97.7	108.8
Magnetic metals	7.6	13.8	15.2
Aluminum	0.5	0.9	1.0
Other metals	0.3	0.5	0.6
Glass	9.0	16.3	18.0
Misc. other solids	3.2	5.8	6.4
Water	25.0	45.4	50.0
Total	100.0	181.4	200.0

The HHV of the as-received municipal waste is 10.70 MJ/kg (4,600 Btu/lb).

Front End System

The first eight steps of processing prepare the raw refuse for the materials recovery systems. Several fractions are isolated, including one that is a finely divided organic "fluff" used as the feedstock for the pyrolysis unit. The elimination from this feedstock of most of the inorganics is an important function of the front end system. The pyrolysis process itself is not affected by these inerts, but the quality of the residual char would otherwise be lowered and maintenance costs for the secondary shredder would be increased.

From storage, unsorted municipal wastes are conveyed to the Primary Shredder, where size reduction to less than 10 cm (4 in.) is accomplished in a heavy duty hammermill. A Magnetic Separator then removes 95 percent of the ferrous metals as the shredded waste is conveyed to the Air Classifier.

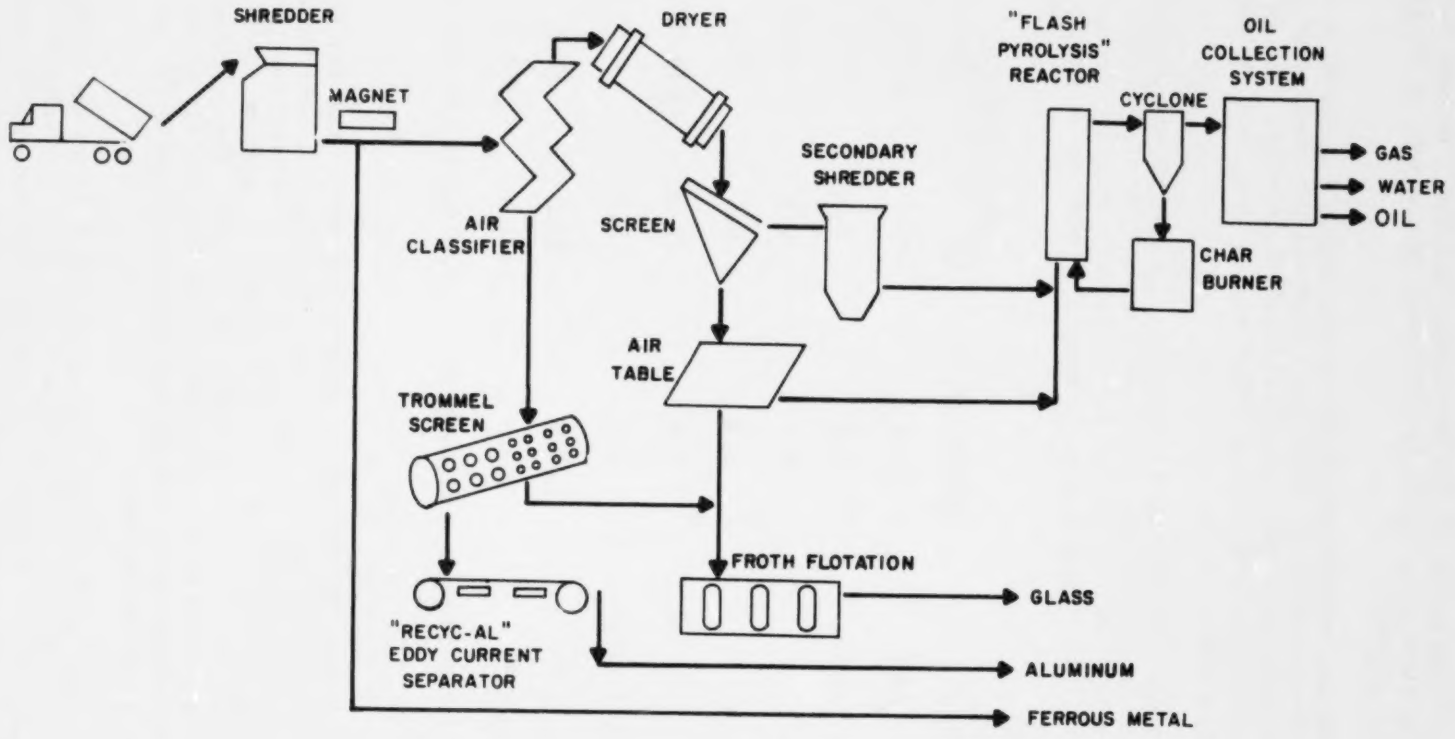

SHREDDER
MAGNET
AIR CLASSIFIER
DRYER
SCREEN
SECONDARY SHREDDER
AIR TABLE
TROMMEL SCREEN
"RECYC-AL" EDDY CURRENT SEPARATOR
FROTH FLOTATION
"FLASH PYROLYSIS" REACTOR
CYCLONE
OIL COLLECTION SYSTEM
CHAR BURNER
GAS
WATER
OIL
GLASS
ALUMINUM
FERROUS METAL

Figure 41. Schematic of Occidental resource recovery system.

The classifier is of the zig-zag type and was designed by ORC. Organics entrained with the inorganic fraction from the air classifier are reclaimed in a later stage of processing. Some 75 percent of the shredded refuse is taken off in the light (overhead) fraction. Approximately 95 percent of the original wet organics are recovered in this fraction and 8 percent of the inerts.

The heavy (underflow) fraction is further treated to recover glass, non-ferrous metals, and entrained organic material. A Trommel (rotating screen) is used for the initial separation. The first section, containing 1.2 cm (0.5 in.) holes, passes the more brittle waste components such as glass, ceramics, rocks, and bones. Typically the composition of this fraction is approximately 50 percent glass and it is conveyed to multi-stage Froth Flotation Tanks after having been ground in a rod mill to a size range of 840 to 44 μm (20 to 325 mesh). Proprietary chemicals in these tanks cause the glass particles to have an affinity for air and they rise through the water on air bubbles while non-glass materials sink. The float material after drying is 99.5 percent glass and represents about 70 percent of the total glass in the original refuse.

A second section of the trommel contains holes that are 10.2 cm (4 in.) in diameter. Material passing through these holes contains 10 percent metal and is conveyed to the "RECYC-AL" Eddy Current Separator" for recovery of aluminum. Material greater than the hole size is returned to the primary shredder feed. A pair of linear induction motors positioned beneath a conveyor belt causes non-magnetic electrically conductive materials to be deflected into a collection system. A travelling magnetic field is generated by the motors, inducing eddy currents in metal pieces such as aluminum. A magnetic field of opposite polarity to that of the motors is produced, resulting in the metal being ejected off the travelling belt. The product collected consists of about 90 percent aluminum and approximately 60 percent of the aluminum originally present in the refuse is thus isolated. The 10% impurities in the aluminum fraction consist of entrapped materials of all kinds from the grinding operation and objects displaced into the collection bin by moving aluminum pieces.

The light fraction from the air classifier is conveyed to a Dryer, a rotary kiln of the type used for removing water from agricultural products, where the moisture level is reduced to about 3 percent. While not essential to the pyrolysis conversion step, this drying does help optimize the conversion and improves separation in the subsequent screening system.

Material not passing through a 1410 μm (14 mesh) Screen has had its inorganic content reduced to about 4 percent. The undersize material contains approximately 65 percent organics and is further purified on an Air Table, where three fractions are obtained. The light fraction has a high organic content and is added to the screen oversize material. A heavy glass-rich fraction is introduced to the glass recovery system. The small intermediate fraction is landfilled.

High heat transfer rates are important to the rapid pyrolysis process. Small particles are required and hence the final front end processing step is to pass the organic fraction through a Secondary Shredder, an attrition mill consisting of counter-rotating disks. The product is quite fine, with 80 percent of it able to pass a 1410 μm (14 mesh) screen. Because of the potential fire hazard in this operation, a pressurized inert atmosphere is maintained within the grinder. Power consumption tests demonstrate approximately equal amounts of power are required in the primary and secondary stages of grinding. As shown in Figure 42, this amounts to 118 to 148 kJ/kg (40 to 50 hp-hr/ton) in each stage.

Pyrolysis System

In contrast to the rather high density moving solid bed converters of the Purox, Torrax, and Georgia Tech pyrolysis systems, the ORC fuel production process occurs in a rapidly moving gas stream. Carried along by an inert turbulent gas (recycled product gas), the finely divided organics from the secondary shredder are heated by hot particles also flowing with the gas stream. These char ash particles are formed and heated in the Char Burner by combustion of the char that is one of the products of pyrolysis. It is introduced into the Flash Pyrolysis Reactor at a temperature of approximately 760°C (1,400°F) and at a mass flow rate five times greater than that of the waste material. Cooling occurs within the reactor so that the actual average temperature for the conversion process is on the order of 510°C (950°F).

The gas exiting the reactor is passed through a mechanical Cyclone, where the ash and the newly formed char are separated. As excess ash builds up during the process, a portion is periodically removed for disposal.

After most particulate matter has been removed from the stream, it is passed into the Oil Collection System where the temperature is rapidly quenched to approximately 80°C (175°F). This is accomplished by spraying a light fuel oil into the gas, effectively stopping any further thermal decomposition. The liquid fuel then settles to the bottom of a decanter, from where it can be moved by pipe to storage tanks. A portion of the water formed in the pyrolysis process is retained with the oil for the purpose of reducing its viscosity.

After clean-up, the gas is compressed for use as (1) the oxygen-free transport medium and (2) fuel for preheating the combustion air into the char heater, the rotary kiln dryer for the coarse-shredded waste, and various process heat needs. All gas finally exits through an afterburner, heat exchanger, and baghouse filter system before it is discharged to the atmosphere.

Typical distribution of the yield of products from the pyrolytic reactor is shown in Table 53, based on dry material entering the reactor exclusive of the gas stream and hot ash. Overall product yields for the total system are discussed below.

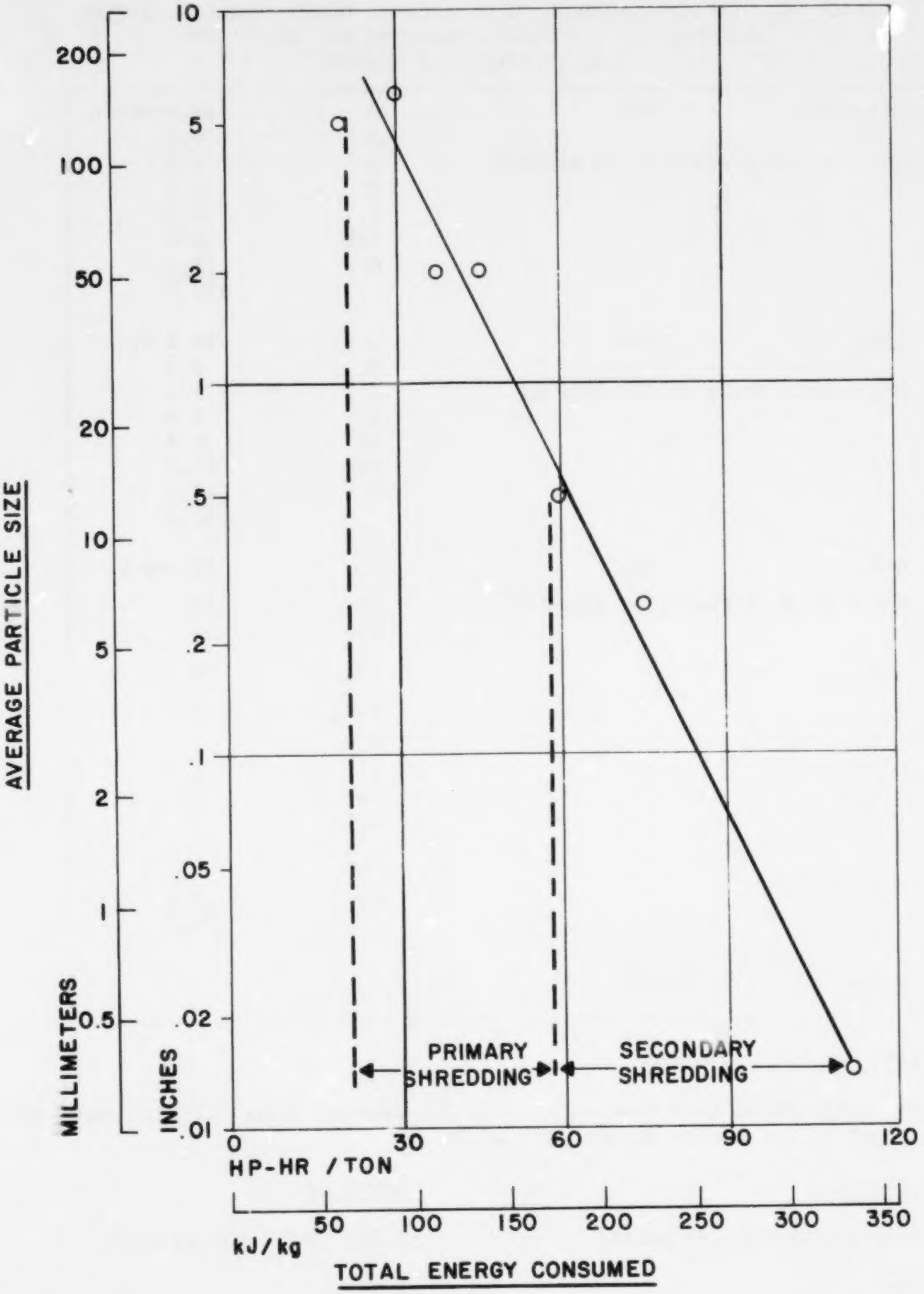


Figure 42. Shredding power as function of size.

TABLE 53. TYPICAL PRODUCTS OF OCCIDENTAL FLASH PYROLYSIS SYSTEM YIELDS AT 510°C (950°F), BASED ON DRY WEIGHT OF FEED TO PYROLYSIS REACTOR

Oil (Dry) - 40%	C	57.0	wt-%
	H	7.7	
HHV = 24.66 MJ/kg (10,600 Btu/lb)	N	1.1	
	S	0.2	
	Cl	0.3	
	Ash	0.5	
	O	33.2	
		100.0	
Char - 20%	C	48.8	wt-%
	H	3.3	
HHV = 19.0 MJ/kg (8,200 Btu/lb)	N	1.1	
	S	0.4	
	Cl	0.3	
	Ash	33.0	
	O	13.1	
		100.0	
Gas - 30%	H_2	12	vol-%
HHV = 14.96 MJ/Nm^3 (380 Btu/SCF)	CO	37	
	CO_2	37	
	CH_4	6	
	C_2H_4	3	
	C_2H_6	1	
	C_3	1	
	C_4^+	2	
	H_2S	0.8	
	HCl	0.2	
		100.0	
Water - 10%			

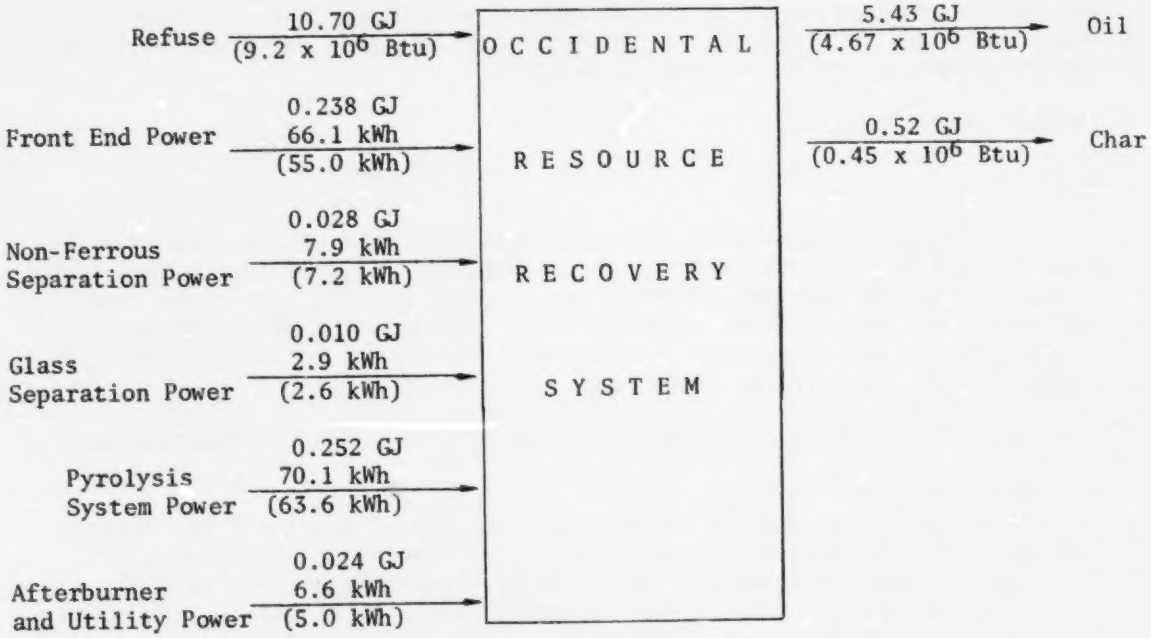
Materials and Energy Balance

The anticipated mass flow output for the process is as follows, based on unity input of raw refuse in any mass units:

Product	Quantity
Oil (containing 14% water)	0.256 (0.221 as dry oil)
Gas	0.441

Product	Quantity
Char/Ash	0.082
Water to Sewer	0.019
Residual to Landfill	0.065
Ferrous Metal	0.072
Glass Cullet	0.061
Aluminum	0.004
Total	1.000

The energy balance of the total system, based on 1 Mg or the parenthetical values for 1 ton* of input refuse, is as follows:


Refuse
10.70 GJ
(9.2 x 10⁶ Btu)
Front End Power
0.238 GJ
66.1 kWh
(55.0 kWh)
Non-Ferrous Separation Power
0.028 GJ
7.9 kWh
(7.2 kWh)
Glass Separation Power
0.010 GJ
2.9 kWh
(2.6 kWh)
Pyrolysis System Power
0.252 GJ
70.1 kWh
(63.6 kWh)
Afterburner and Utility Power
0.024 GJ
6.6 kWh
(5.0 kWh)
OCCIDENTAL RESOURCE RECOVERY SYSTEM
5.43 GJ
(4.67 x 10⁶ Btu)
Oil
0.52 GJ
(0.45 x 10⁶ Btu)
Char

The energy recovery efficiency is based on the assumption that a heat equivalent portion of the product oil would be used to generate electricity (at a net plant heat rate of 10,550 kJ or 10,000 Btu/kWh). This energy penalty is assessed against the product and this value then compared to the original energy content of the refuse. If only the oil is considered as a useful product, this mathematically (in English units) becomes:

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*Note that the English units are not factored conversions from SI (which would imply an input of 1.1023 tons), but for convenience are based on the convention of 1 (exactly) ton input.

$$\eta = \frac{4.67 \times 10^6 - 1.39 \times 10^6}{9.2 \times 10^6} \times 100 = 35.6\%$$

If the output energy is considered to include that in the char, a material that would be difficult to sell as a fuel because of its high ash content, the energy recovery would increase by 0.52 (0.45×10^6 Btu) and efficiency would then be 40.5%. Comparison to efficiencies of other processes, even pyrolysis systems, must be attempted only with a full recognition of the worth of final products. That some 60% of the originally totally wasted energy is required to operate a process able to "create" large quantities of a synthetic fuel oil should not be considered discouraging, but viewed as a factual description of a given chemical system. Further energy efficiency can be attributed to the savings that result from recovery of glass, ferrous metals, and aluminum, in that manufacture of new materials in contrast to recycling old ones is a more energy-intensive process. No consistent set of assumptions has been yet developed for quantification of the "inherent" energy in the recovered materials, but the additional 3.37 GJ/Mg (2.90×10^6 Btu/ton) sometimes cited by Occidental is an entirely reasonable value and would raise the efficiency to 67.2% (excluding char).

PRODUCT CHARACTERISTICS

Oil

As with petroleum itself, the oil produced in the ORC process is a complex mixture of molecular weights and structural configurations. While its chemistry has not been investigated to any great detail, sufficient characterization has been made to establish the probable value of the liquid as a utility fuel. Key properties of the product are shown on Table 54 along with those of No.6 fuel oil for comparison.

Important differences between the two oils that can be noted include:

Elemental Analysis--

The high oxygen content of the pyrolytic oil, a result of the largely cellulosic composition of the original waste, results in a decreased HHV compared to normal hydrocarbon fuels and causes marked solubility (60%) capability of the oil. Water is retained to decrease viscosity. The oxygen content, in addition to the chloride level, results in some acidity of the product; storage should present no particularly difficult problem and details of materials to be used will be established during the El Cajon demonstration plant study. An additional characteristic that thusfar is attributed to the high oxygen content is that extended high temperature storage causes a further increase in viscosity and it is recommended the oil be maintained below 71°C (160°F) until just before atomization. The low sulfur content is a property of the pyrolytic oil that makes it an attractive RDF. The low ash content, being markedly less than solid forms of RDF, is another important feature of the liquid fuel.

TABLE 54. TYPICAL PROPERTIES OF NO. 6 FUEL OIL AND OCCIDENTAL'S PYROLYTIC OIL

Composition, wt-%	No. 6 Oil	Pyrolytic Oil
C	87.5	57.0
H	10.5	7.7
S	0.7-3.5	0.2
Cl	-	0.3
Ash	0.5	0.5
N		1.1
O	2.0	33.2
Specific Gravity	0.98	1.30
Heating Value		
MJ/kg	42.33	24.66
MJ/dm^3	41.47	32.03
Btu/lb	18,200	10,600
Btu/gal	148,800	114,900
Pour point, °C (°F)	18-29 (65-85)	32* (90*)
Flash point, °C (°F)	66 (150)	56* (133*)
Viscosity		
mm^2/s at 88°C	48	160*
SSU at 190°F	340	1,150*
Pumping temperature, °C (°F)	46 (115)	71* (160*)
Atomization temperature, °C (°F)	104 (220)	116* (240*)

*Pyrolytic oil containing 14% water, as marketed.

Specific Gravity--

The pyrolytic oil has an unusually high density, some 34% higher than that of the usual fuel oil. The ORC product has a higher energy content per volume than any other refuse-derived fuel, a factor that will reduce its transportation costs relative to other RDF's.

Heating Value--

While even on a volumetric basis the HHV of the pyrolytic oil is 23% less than that of fuel oil, it is higher than an average coal and if used in conjunction with a liquid fossil fuel, a substantial portion of the total heat input to the furnace can be supplied by it without any major modifications to the system or its steam-generating characteristics.

Flow Properties--

The presence of 14 percent water alters flow properties of the pyrolytic oil sufficiently to permit it being handled with conventional equipment, although the Occidental product remains more viscous than No. 6 oil. The effect of temperature is greater for the synthetic oil, however, such that the atomization temperatures are only 12°C (20°F) apart.

The combustion properties of oil produced in the pilot plant were briefly examined in research burners by Combustion Engineering, Inc. Blends of pyrolytic oil of 25 and 50 percent by volume with No. 6 oil derived from Alaskan crude were used. Such blends eventually separate because of the solubility characteristics of the oxygenated oil, but are stable for several hours. It was established that ignition stability is equal to the fossil oil alone and that combustion is successful with properly designed fuel handling equipment. At air levels over 2 percent excess oxygen, there were negligible quantities of unburnt carbon in the stack emissions.

Glass

The mixed color cullet recovered from the froth flotation tanks contains in excess of 99.5 percent glass and represents about 70 percent of the original glass content of the as-received municipal waste. The material can be drained dry to 5-10% water content or further dried, depending on relative costs of heat energy as compared to transportation. A typical particle size distribution is as follows:

Size			
μm	Tyler Mesh	Wt-%	Cumulative Wt-%
>833	+20	0	0
833 to 495	-20 +32	11	11
495 to 295	-32 +48	41	52
295 to 246	-48 +60	13	65
246 to 147	-60 +100	20	85
147 to 74	-100 +200	12	97
<74	-200	3	100

This cullet may be directly employed for glass container manufacture, with some 15 percent less energy being required for melting than with glass raw materials. Hand blown cruets and molded containers made by a leading glass manufacturer were free of any "stones" or other defects. The mixed color composition of this cullet could present some marketing problems and Occidental is continuing to examine glass color sorting techniques. While up to 20 percent of the mixed cullet may be added to amber color batches and 30 percent to green batches without significantly affecting final product color, approximately 65 percent of container manufacture now calls for flint (colorless) glass. A large resource recovery facility might produce more mixed cullet than required by the colored glass industry in the regional area, thus limiting revenues from this product source.

Metals

The quality of ferrous metals collected by the magnetic separation equipment is typical of the many other facilities using this technique. Residual food wastes, coatings, and entrained paper products contaminate the metals and soft metals used for ferrous soldering and corrosion protection also are present. The ideal market is sales to a chemical de-tinner who in turn sells the steel, usually as No. 1 Dealer Bundles.

The metal isolated by the Occidental RECYC-AL eddy current device contains about 90 percent aluminum, with the principal impurities being copper, zinc, iron, and miscellaneous other metels such as tin, lead, nickel, chromium, etc. Beverage container aluminum must meet stringent specifications in order to be used with modern production equipment and hence the prime market for this mixed metal will be the secondary aluminum alloy industry. These manufacturers blend available salvage stock to produce desired alloys and the Occidental non-ferrous metal fraction will present no problems for them.

ENVIRONMENTAL CONSIDERATIONS

Recent experience in other facilities has indicated that principal environmental problems occur on start-up of a new full-scale waste processing facility. This same experience, however, demonstrates that solutions exist within the current state-of-the-art and additional expenditure will typically permit operation of the plant within applicable local and EPA regulations. While development tests to date have not shown any effluents or noise are produced for which design features have not been incorporated into the El Cajon plant, it is believed that the type of problem that might be encountered should be solvable with addition of some extra control equipment. A specific EPA experimental investigation or environmental effects of this facility has been scheduled.

All front end handling and processing steps producing an air stream containing particulate matter are controlled by passing the gas through a baghouse fabric filter system. Effluents from the char burner and waste drier are passed through an afterburner, fueled by a portion of the pyrolysis recycled off-gases, where any combustible matter is exposed to a minimum of 649°C (1,200°F) for at least 0.5 second under oxidizing conditions. The gas then passes through another baghouse before being released to the atmosphere. A process heater within this system supplies heat to the dryer and various process lines.

Estimated emissions from the afterburner baghouse are:

Component	Concentration
SO_2	700 ppm (wt)
NO_x	8 to 1,000 ppm (wt)
HCl	100 ppm (wt)
Particulates	0.12 g/Nm^3 (0.05 gr/SCF)

The wide range in the value for nitrogen oxides is a result of the extremes of assuming (1) only atmospheric nitrogen is fixed according to the known thermodynamics of this reaction and (2) that in addition all nitrogen entering the afterburner is involved in the equilibrium.

Two contaminated water streams exist. That from the glass recovery system is the larger of the two, but tests have verified that standard floculation reagent addition, clarification, and filtration brings the water to a quality level permitting discharge to a sewer system. The second stream, totalling approximately 3.6 Mg/d (4 TPD) for the demonstration palnt, results from the product quenching and collection system. This effluent can contain up to 100,000 ppm of COD. Limited experiments indicate the organic contaminants are fully biodegradable, but typical local regulations would forbid discharge of this liquid directly to a sewer system. Reduction of the COD load would consist of the use of one of several standard biological waste water treatment systems. Occidental has suggested that in some applications of the recovery plant sufficient heat might be available for afterburning the entire water effluent.

Residual solids amount to 13 to 16 percent of the weight of the input refuse. About half of this is inert ash from the pyrolysis system and the remainder is rejected material from the air table and glass recovery system. The inert portion of this latter is approximately 50 percent.

Noise, as with other waste processing systems involving front end treatment, is principally from the size reduction equipment. Sufficient experience in attenuation of this sound energy has now been obtained that no problems are anticipated at the demonstration plant.

ECONOMICS

The 181 Mg/d (200 TPD) resource recovery plant at El Cajon is intended to be a facility for demonstration of the technological and environmental feasibility of the Occidental process. It incorporates a rather high degree of design versatility and the instrumentation/control system is capable of data compilation not required for a production plant. The process, largely due to its advanced materials treatment sub-systems, is acknowledged to have a high cost sensitivity for input capacity and the demonstration plant's size is below the level where good returns on investment would normally be obtained. Accordingly, the discussion of the economics of the system here is limited to processing capacities of 907 Mg/d (1,000 TPD) and 1814 Mg/d (2,000 TPD). The composition of the municipal solid waste and the product output ratios are those previously presented.

Operational Characteristics

It is assumed that waste will be received 5-1/2 days per week and processed 7 days per week. The front end system will be operated 16 hours per day and the remainder of the plant 24 hours per day. An annual plant utilization factor of 0.90 has been used. Table 55 shows the annual processing capacities of the two plants.

TABLE 55. ANNUAL PROCESSING CAPACITIES OF 907 AND 1814 Mg/d (1,000 AND 2,000 TPD) PLANTS (0.90 UTILIZATION FACTOR)

	Feed Input				Output			
	Smaller Plant		Larger Plant		Smaller Plant		Larger Plant	
Component	Gg	10^3 ton	Gg	10^3 ton	Gg	10^3 ton	Gg	10^3 ton
Organics	162.2	178.8	324.4	357.6				
Magnetic Metals	22.7	25.0	45.4	50.0	21.5	23.7	42.9	47.3
Aluminum	1.4	1.6	2.8	3.2	1.2	1.3	2.4	2.6
Other Metals	0.9	1.0	1.8	2.0				
Glass	26.8	29.6	53.6	59.2	18.2	20.0	36.4	40.1
Misc. Solids	9.5	10.5	19.0	21.0				
Water	74.6	82.2	149.2	164.4				
Oil (14% water)					76.3	84.1	152.7	168.3
Char/Ash					24.4	26.9	48.9	53.9
Solid Residue					19.4	21.4	38.8	42.7
Water to Sewer					5.7	6.2	11.3	12.5
Flue Gas					131.2	144.6	262.4	289.3
Total	298.2	328.7	596.4	657.4	298.2	328.7	596.4	657.4

Capital Costs

Table 56 lists the various elements of 1976 capital costs for the two plants. The capital recovery factor of 0.10567 used for the annualized cost is based on a 20 year useful life of the plant and an 8-1/2% interest rate. Costs attributable to capital amount to $10.13 and $7.63/Mg of input waste for the 907 and 1814 Mg/d plans respectively ($9.19 and $6.92/ton).

TABLE 56. 1976 CAPITAL COSTS FOR 907 AND 1814 Mg/d (1,000 AND 2,000 TPD) PLANTS

Cost Element	Cost, $ (000)	
	Smaller Plant	Larger Plant
Land	100	130
Site Preparation	35	46
Design	2,160	3,030
Construction and Installation	12,700	19,300
Real Equipment	8,100	12,400
Other Equipment	615	808
Contingencies (@ 10%)	2,371	3,571
Startup and Working Capital	2,010	3,025
Financing and Legal	514	775
Total Capital Investment	28,605	43,085
Annual Capital Cost (20 years, 8-1/2%)	3,023	4,553
Capital Cost, $/Mg	10.13	7.63
Capital Cost, $/ton	9.19	6.92

Operating Costs

The following factors were used in developing the operating costs:

Labor (incl. benefits)	$7.00/h
Fuel	$0.35/gallon
Electricity	$0.02/kWh
Water	$0.50/1,000 gallons
Insurance, Fees, and Prof. services	$1.00/input ton
Taxes	0.75% of plant investment
Maintenance and repairs (incl. labor)	7% of plant investment
Parts and supplies	0.75% of plant investment
Residue transportation and disposal charge	$7.50/ton

Table 57 shows the annual operating costs, indicating per Mg (ton) costs to be \$19.07 (\$17.30) and \$14.52 (\$13.17) for the two capacity plants.

Revenues and Net Operating Costs

Table 58 shows possible revenues that might be realized from the two plants. Material sales prices are those established by ORC market research and transportation costs based on 25 percent of expected revenues have been allowed. The pyrolytic oil sales price is estimated to be \$1.75/GJ (\$1.85/10^6 Btu) with transportation costs of \$0.008/dm^3 (\$0.03/gallon).

TABLE 57. 1976 ANNUAL OPERATING COSTS FOR 907 AND 1814 Mg/d (1,000 AND 2,000 TPD) PLANTS

	Cost, \$ (000)	
Cost Element	Smaller Plant	Larger Plant
Labor	1,604	1,925
Fuel	10	20
Electricity	832	1,664
Water	56	112
Maintenance and Repairs	1,826	2,750
Parts and Supplies	195	295
Residue Disposal	193	386
Overhead and Mobile Equipment Operation	444	556
Property Taxes	195	295
Insurance, Fees, and Professional Services	329	657
Total	5,684	8,660
Operating Cost, \$/Mg	19.07	14.52
Operating Cost, \$/ton	17.30	13.17

TABLE 58. PRODUCT REVENUES

Material	Revenue $/ton	Shipping $/ton	Fraction Recovered	Revenue $/ton input
Magnetic Metals	55	13.75	0.072	2.97
Glass	21	5.25	0.061	0.96
Aluminum	400	100.00	0.004	1.20
Oil	*	*	*	7.24
Total				$12.37

* Based on $\$1.85/10^6$ Btu, shipping costs for $\$0.30/10^6$ Btu, and 4.67 x 10^6 Btu recovered/ton input.

Net operating costs can be summarized from the above as follows (assuming no revenue from drop charges):

	907 Mg/d (1,000 TPD) Plant		1814 Mg/d (2,000 TPD) Plant	
Capital Cost	$10.13/Mg	$9.19/ton	$7.63/Mg	$6.92/ton
Operating Cost	19.07	17.30	14.52	13.17
Total Cost	29.20	26.49	22.15	20.09
Revenue	13.64	12.37	13.64	12.37
Net	$15.56/Mg	$14.12/ton	$8.51/Mg	$7.72/ton

SECTION 10

CAPACITY-COST SUMMARY

Ideally, a master figure could be prepared indicating the costs of various size plants associated with each type of processing technology. Two key factors detract from developing such presentations. The first concerns the matter of ranking of systems that has been previously discussed. As an example, an RDF plant, having no capital costs associated with it for the actual energy recovery step, would appear to be the most economically attractive process on such a multi-candidate figure. In reality, selection of the best facility for a specific location is of course much more complicated than this. The second difficulty involves the matter of the great variety of credits that can be claimed for the fuel value, materials, and the charge to be made for refuse disposal. Proper selection of values can tend to favor particular systems and presents a bias in the apparent results presented.

Sufficient information exists within this report for construction of such a figure by interested organizations. Interpretation of inter-system comparisons should be approached with caution unless consistent data based on actual local information is used.

Some of the analyses made for the separate candidates do lend themselves to a graphical presentation that does aid in a better understanding of waste-to-energy systems. Such figures are presented within this Section.

Figure 43 shows the range of capital costs as a function of daily processing capacity for facilities for preparing RDF and using the supplementary fuel in existing coal-fired boilers. Extrapolation somewhat above 2360 Mg/d (2600 TPD) can be made with rather good accuracy, although practical problems of collection truck traffic congestion and queuing, waste availability, etc., occur near the point and individual studies must be made to establish true local costs. Economics of scale do not necessarily continue and a 4720 Mg/d (5200 TPD) plant would approximate the costs of two 2360 Mg/d (2600 TPD) facilities so closely that consideration should be given to siting separate plants near two centers of waste generation. Extrapolation below about 545 Mg/d (600 TPD) can lead to high percentage inaccuracies in that the fixed costs of design and construction, high unit equipment costs, and any degree of processing line redundancy have great effects on unit costs.

The cost information shown in Figure 43 is based on specific studies conducted by Parsons for 3 Mid-Western clients. Each of the originally-derived design/cost packages was adjusted to a uniform set of assumptions of pricing currentness, financial structure and fees, type of equipment, and operating schedule. One facility, for example, was designed to contain an aluminum

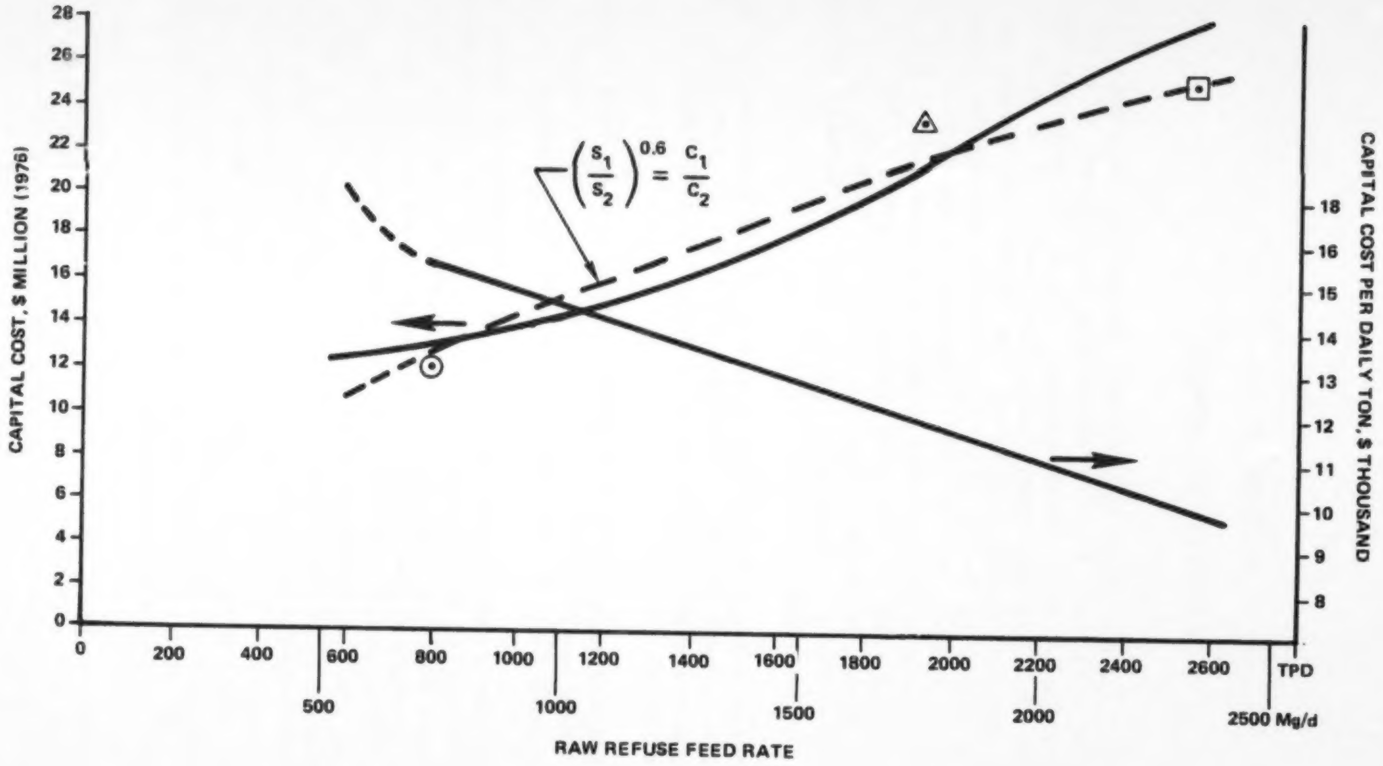

Figure 43. Supplementary fuel processing plant (RDF) capital costs.

recovery processing step, and all costs associated with this sub-section were eliminated so that ferrous metal (and RDF) was the only material resource isolated at each plant. Another plant was sited at a distance form the power plant and in this case the costs for trucks and loading facilities were deleted to make the standard case one of an RDF plant immediately adjacent to the power client. The assumptions used were as follows:

- Mid-1976 costs
- Daily processing capacity defined to be that possible by operating at maximum throughput 16 hours per day (maintenance to be performed during 3rd shift and week-ends)
- Processing to consist of receiving, shredding to 100% less than 38 mm (1.5 in.), removal of magnetic metals, air classification, and transfer to adjacent power plant storage
- Power plant equipment sized to operate boilers continuously and to consist of receiving piping, beehive-type storage and retrieval system, and modifications to furnaces to handle supplementary fuels.
- No land costs are included because of the high degree of variability throughout the nation
- Sum of interest during construction, working capital, and start-up costs is 20% of remaining capital costs
- Design and construction management to be accomplished by a private firm using ASCE rate structure

The above assumptions resulted in the following capital costs:

Capacity		
Mg/d	TPD	Capital Cost, $
726	800	12 060 000
1742	1920	23 780 000
2322	2560	25 310 000

These values are plotted in terms of both the absolute capital cost and on a daily unit weight basis. The dashed line added represents the function oftentimes found to describe capital costs, where these costs are proportional to the 0.6 power of the capacity. In the equation S_1 and S_2 are the sizes of two plants having costs of C_1 and C_2 respectively. From the limited data used to develop this figure, the 0.6 power straight line could adequately describe costs over the range of interest. The curve faired in represents the probable realistic case where at lower capacity levels, fixed costs of design and high equipment costs lead to increasing costs per unit and where at some middle level the greatest change in the economies of scale occur. Eventually at some high capacity, a curve reversal might occur where the size of the operation leads to cost inefficiencies.

The City of Chicago RDF facility can be used to illustrate the cost sensitivity of varying throughput at a given size plant. The reliability gained by redundancy and scheduled maintenance down-time is vital to the success of an operation, but of course the cost of this reliability is reflected in higher unit costs as processing capacity is reduced. Figure 44 shows this effect over the range of 725 to 1633 Mg/d (800 to 1800 TPD).

Figure 45 shows probable capital costs for flash pyrolysis facilities for producing liquid fuel from MSW over an input capacity range of 600 to 2200 TPD. Until operating experience is gained at the El Cajon plant of Occidental Research Corporation (ORC), the 0.6 exponent capacity-cost curve shown will serve to estimate costs for such plants.

Within Figure 46 are shown adjusted capital cost estimates for several waterwall incinerators. The square represents the 600 TPD Hamilton, Ontario, plant; an additional 3% has been added to the $15.4 million new cost discussed in this report to adjust that value to mid-1976. The point within the triangle is based on costs associated with the 720 TPD plant of Nashville Thermal Transfer Corporation. From their original cost of $16.5 million has been deducted $4 million for the distribution piping network and an inflation factor of 1.24 then applied. The current expenditures of $5.7 million were then added to yield a probable 1976 cost of $21.2 million. The circles represent 12% inflated adjustments made on values within this report for facilities based on the RESCO, Saugus, design. The 1200 and 1500 TPD values at the same cost result from the fact that the lower capacity is a nominal one and the possibility exists that the present plant might be capable of operating at 1500 TPD. The curve shown for the capital cost per daily ton is based on the smoothed curve indicating costs are proportional to the capacity to the 0.85 power. Several other costs available to Parsons fall reasonably well on this same curve.

The capital cost-capacity curves for the two pyrolytic gasifiers discussed in Sections 7 and 8 are shown in Figure 47. The plotting of Torrax and Purox costs on the same figure illustrates the care with which such figures must be read. While it would appear that the six points used in this curve would fit the same equation, the values used for the Torrax system represent costs for facilities whose output is steam, while the Purox plants produce a medium heating value gas requiring additional facilities for energy utilization.

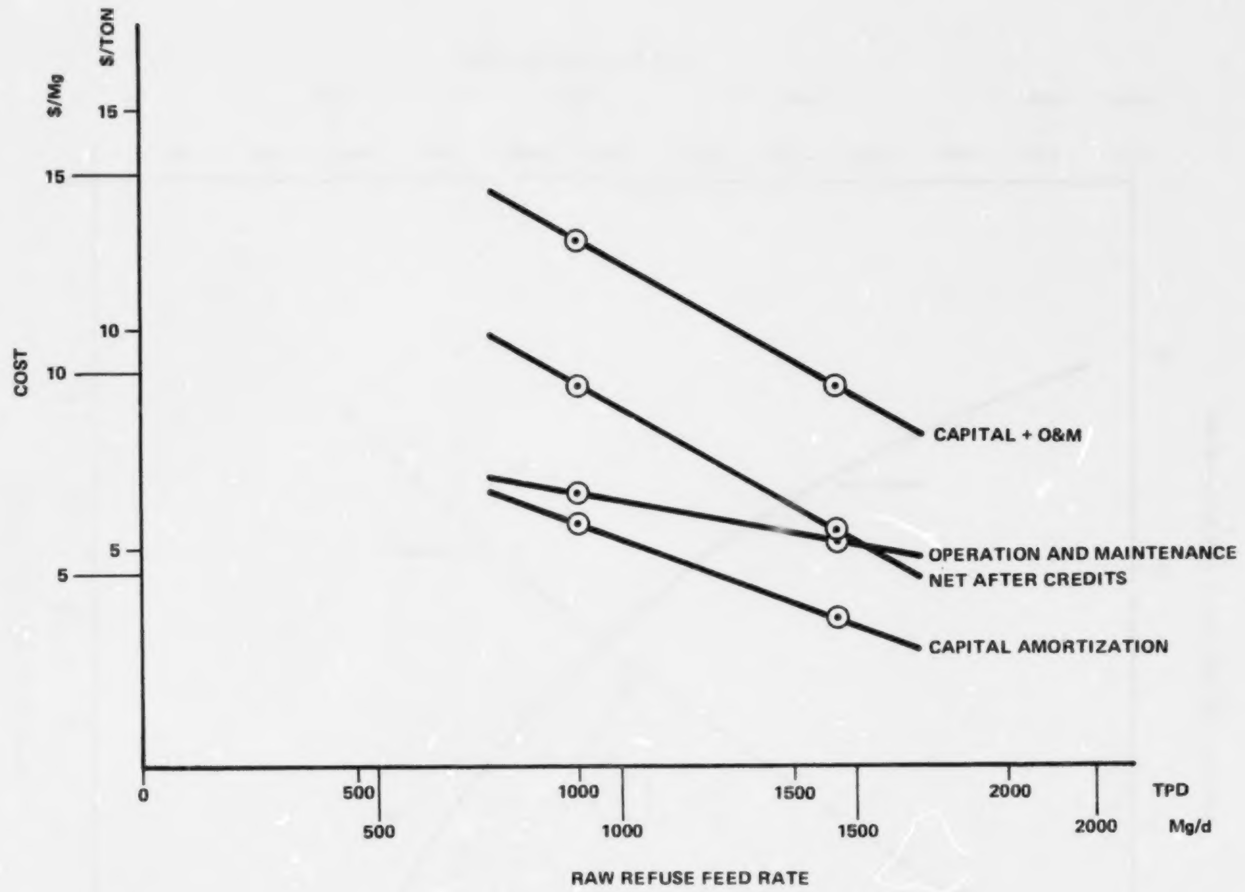

Figure 44. Costs vs. processing throughput for existing facility (City of Chicago Supplementary Fuel Plant).

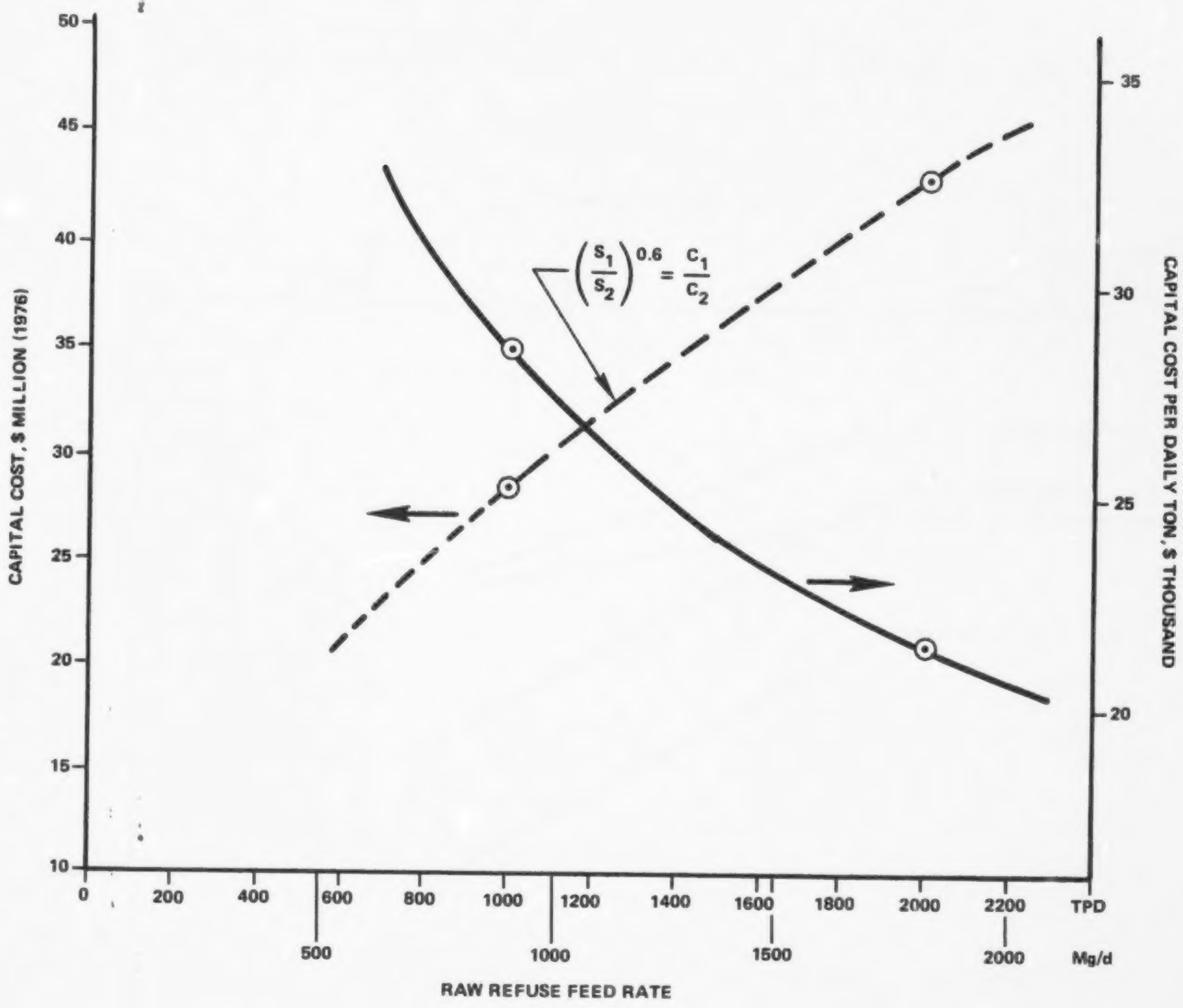

Figure 45. Capital cost vs. capacity of flash pyrolysis facility.

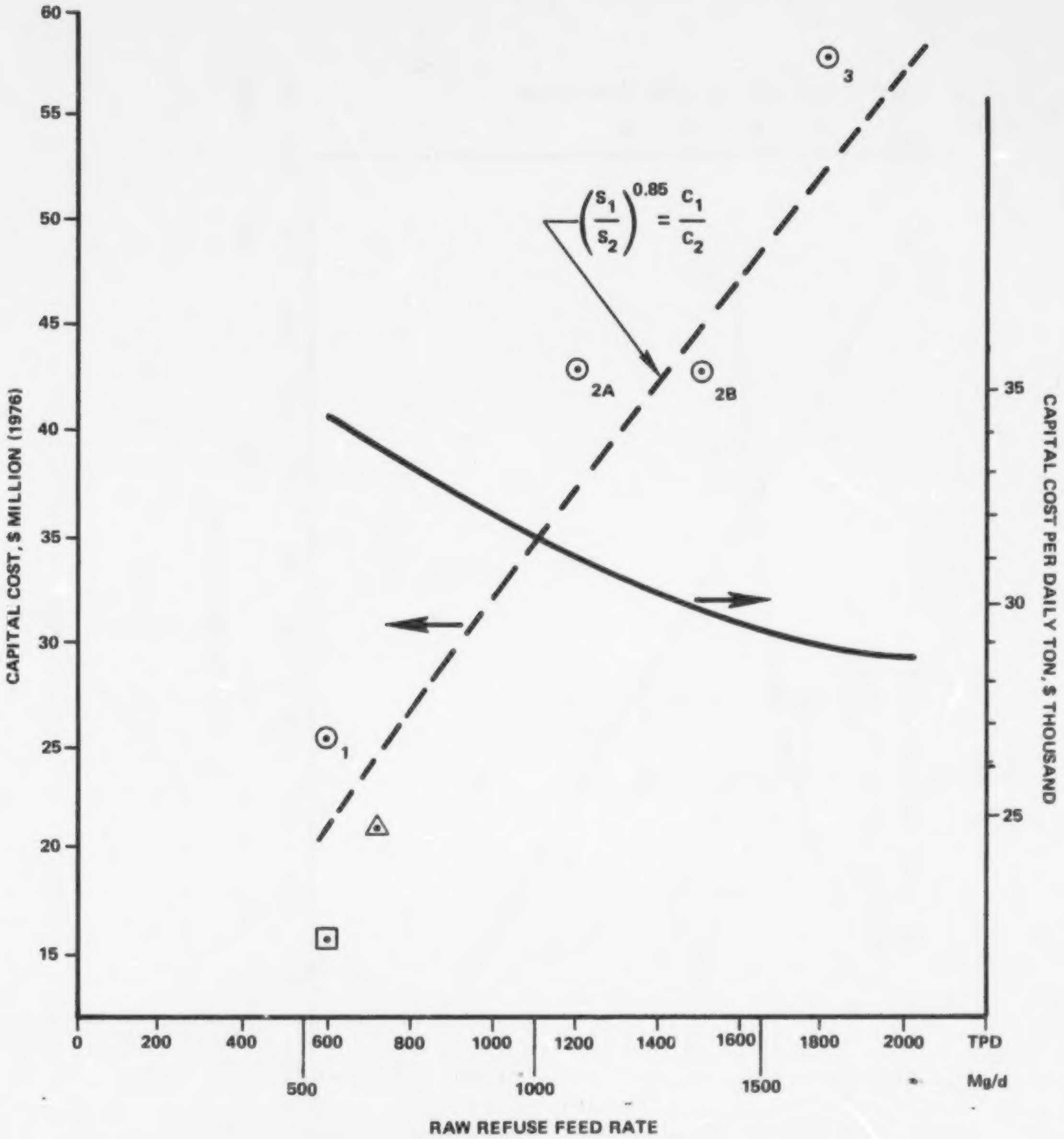

Figure 46. Capital cost vs. capacity of waterwall incinerators.

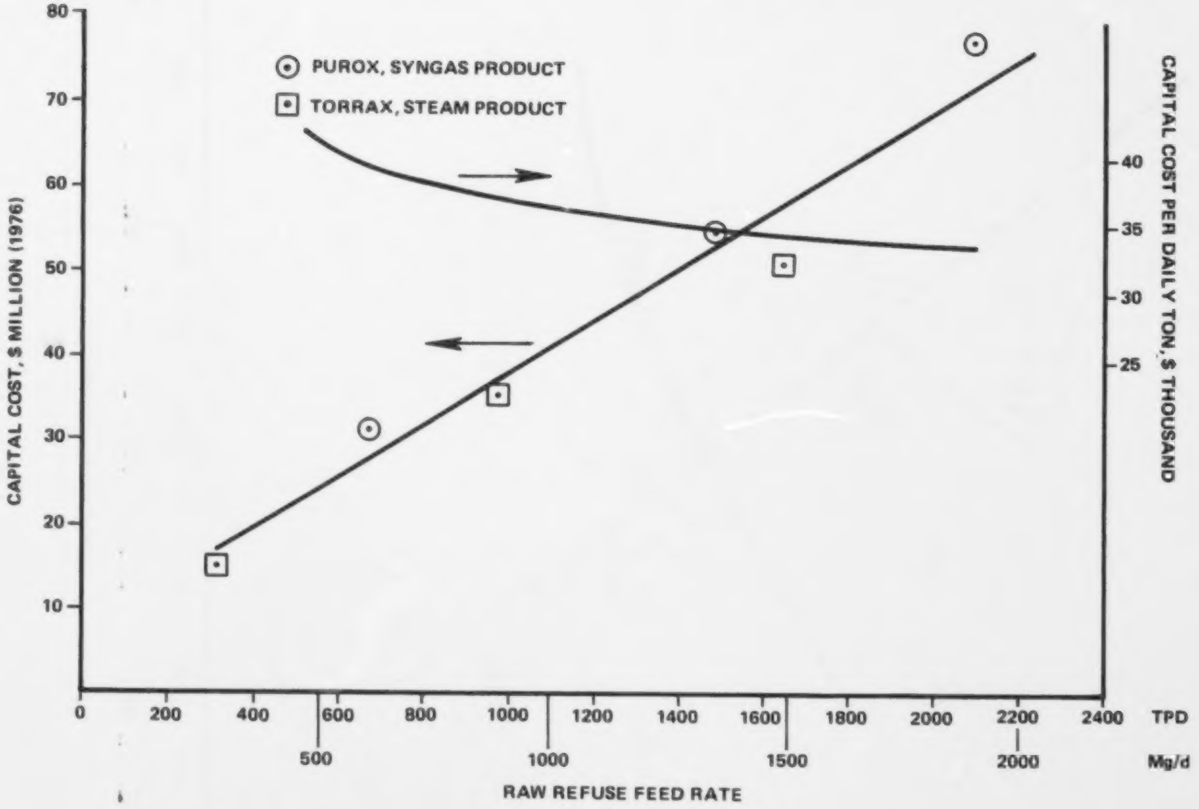

Figure 47. Pyrolytic gasifier capital costs.

SECTION 11

GENERAL CONCLUSIONS

Conclusions and recommendations developed during this project are discussed in this Section under three categories: Planning Factors, General System Needs, and Waste Material Utilization. The first concerns policy and planning matters affecting waste-to-energy technology while the second discusses areas that apply to more than one system. The third lists conclusions on how the characteristics of U.S. wastes influence their utilization as energy sources. Conclusions peculiar to a specific facility or type of conversion system have been presented within Sections 3 through 9.

PLANNING FACTORS

Issuance of a government document presenting probable interactive effects of economic and trade factors on energy costs is recommended. Private organizations and local governments must prepare an expenditure/revenue analysis over a 10 or 20-year period to determine the relative advantages of a waste-to-energy conversion system versus alternative disposal means. Income from the sales of energy will be an important source of revenue. The local planner now faces difficulties in locating officially sanctioned and consistent forecasts of absolute future costs of alternative energy forms and long-term revenue forecasts are therefore difficult to make. However, sensitivity analysis would at least reveal the relative effect of a variety of economic factors on projected cash flow for the several types of waste conversion facilities.

A manual entitled "Standardized Methodology for the Cost Estimation of Commercial-Scale Waste-to-Energy Conversion Systems" would also be of great benefit to a number of organizations. This document must be more than an accounting system for establishing uniform cost factors. It should enable a developer utilizing the recommended detailed procedures to approach a client with sufficient information to permit an unbiased economic comparison of alternative conversion processes.

To date there has been very little data published on environmental emissions and effects from conversion plants. Past and on-going environmental test results should be immediately documented and issued to those concerned, along with applicable regulations and a brief review of the best available control technology. Current projects for compiling information and making new measurements should be continued and reports issued whenever new types of facilities or systems become operational. Regulatory hearing boards issuing permits for new conversion plants often require comparisons of environmental effects of alternative disposal methods. Such information, including data for sanitary landfill operations as well as health and safety considerations, should be made available in a summary document.

Nontechnically trained personnel are often required to make key decisions as to whether a new conversion facility should be financed and constructed. A document should be prepared to assist decision-makers in understanding the critical factors to be examined, relative advantages of various alternatives, and the ramifications of their decisions. Summary reviews of technological, environmental, and financial considerations should be included.

Even the expert in waste-to-energy conversion technology must presently review an inordinate quantity of information to maintain his skills. A critically edited comprehensive annual publication by EPA and ERDA would significantly reduce the burden of literature review; the document should not be restricted to existing government-funded projects.

GENERAL SYSTEM NEEDS

Front end processing prior to obtaining energy from waste materials is largely adapted from other industries. Much remains to be accomplished in establishing the proper type of equipment to be used and in improving efficiencies. Development activities in the areas of storage and retrieval, size reduction, drying, transfer, and component separation must be pursued to increase throughput for a given energy expenditure and to recover higher purity material fractions. In most cases, initial research should be conducted using 100% paper or similar material in order to learn more about the fundamental controlling parameters of the process. Water content should then be changed over a range of "0" (dried at 100°C) to 40% to establish the effect of this common variable. Only after these tests have been completed should greater heterogeneity be investigated through incorporation of the other components typical to the particular waste. Investigations should include:

- Concepts for improved receiving and initial transfer of wastes to reduce capital, operating, and maintenance costs. Bridging of raw wastes in storage, and belt transfer at high unit loadings are particular problems.

- Improvements in equipment for the storage and retrieval of RDF and means of controlled introduction into furnaces as a function of heating fraction. A method of continuous flow measurement is also needed.

- Means of reducing energy consumption and high maintenance costs of size reduction equipment. Current investigations into improving the technology should be continued and safety (fire and explosion) aspects further considered.

- Means to avoid empirical adjustment of air classification systems for isolating the combustible fraction of wastes to give the best possible yields of RDF. The systems are expensive and need improvements in both the percentage recovery and purity of the fractions.

- Other processes for separation of mixed wastes into their components, not necessarity intended for energy recovery, that would influence overall plant economics and improve efficiency.

- Partial removal of water (down to 2 to 10%) from the fuel to increase boiler efficiency. Studies need to be conducted to improve the efficiency of dryers for waste materials.

The characteristics of various waste-derived fuels are not yet sufficiently well defined to permit a meaningful comparison of their relative advantages. An independent laboratory should be engaged to determine the physical, mechanical, chemical, and biological properties of these fuels under conditions of transport, storage, and usage. The evaluation should include RDF as manufactured; RDF/coal and RDF/oil blends; agricultural waste-derived fuels from various sources and having varying physical properties; and liquid fractions from pyrolytic systems. Stability, corrosive properties, health effects, and applications in energy-releasing equipment must all be studied. It is recommended that research be conducted to modify any adverse properties that may exist.

Preengineered design of transportable sections of a modular processing/production facility often offers important capital cost savings. Economies of scale and an experienced work crew at the manufacturing plant reduce costs and eliminate expensive custom engineering at the client's site. While some waterwall combustion systems employ this practice to an extent, the concept has not generally been applied to the waste-to-energy conversion field. It is Parsons' conclusion that an engineering analysis be conducted to determine whether significant cost savings from modular design might indeed result.

The design of pyrolytic conversion equipment is hampered by a lack of relevant data on the complex chemical reactions involved and the effects of physical variations on this chemistry. This often leads research workers investigating new variations of a waste pyrolysis process to assume their methods will offer dramatic breakthroughs in developing new energy sources. Such claims typically have proven unrealistic when scale-up tests reveal actual yields and thermal conversion efficiencies. Several EPA-sponsored projects are now in progress to obtain further information for the generalized pyrolysis process. Other R&D related to specific systems is being conducted at industrial and university laboratories. Data derived from these studies will also contribute to further knowledge of the field. On the basis of Parsons' surveys, it is concluded that much remains to be accomplished in pyrolysis technology and that government-supported investigations should continue for a number of years. Periodic publication of up-to-date information on the nature of the waste-to-energy market and factors leading to commercial profitability will encourage private research.

The R&D recommended above is directed to development of fundamental information on pyrolysis chemistry. Applied pyrolysis studies are also needed to advance the state of the art. It is recommended that the following be pursued:

- The effect of mixed types of wastes on pyrolytic yields and process economics should be established. MSW, sewage, commercial, industrial, and agricultural/forestry wastes should be used as feedstocks in varying ratios (and water content) to determine operational limits and to provide direction for future commercial activities.

- The effect of wastes as additives to present coal conversion systems should be determined.

- Superior methods for introduction of wastes into pyrolytic reactors, particularly those such as fluidized bed systems operating above atmospheric pressure, must be developed. Likewise, removal of char or slag remains as a problem.

- Use of pyrolysis for processing 10 to 100 Mg/d (11 to 110 TPD) wastes should be investigated.

- Alternative methods of protection against the temperature extremes and the corrosive pyrolytic products should be investigated. The thermal and chemical environment within a pyrolytic reactor has led to selection of costly construction materials and techniques.

- Combustion devices designed to operate with relatively heterogenous fuels must be further developed. Those pyrolytic systems yielding hot off-gases containing suspended solid and liquid combustibles operate most efficiently when the heterogeneous fuel is immediately combusted and the total heat recovered in an exchange system.

Although often associated with the PUROX pyrolysis system, the research required to establish process economics of converting pyrolysis off-gases to methane, methanol, or ammonia actually applies to a broader area. The chemistry (and economics) involved in converting mixtures of carbon monoxide and hydrogen to the three named compounds is quite sensitive to the ratio of CO to H_2 and to the presence of the usually simultaneously present carbon dioxide, water, hydrocarbons, and sulfur compounds. Much is known of this chemistry, but pyrolytic off-gases, including those from oxygen-blown reactors, have compositions markedly different from the syngas used to date. No accurate predictions can be made regarding the effect of these differences on catalyst life, degree of purification required, equipment size, and product yield. To investigate all controlling parameters for the possible range of pyrolytic off-gases would be very expensive and therefore is not recommended. What is recommended is the statistical design of a test program that would use the PUROX gas as a base case and permit adjustments around that composition to learn the principal effects of other off-gases on the economics of conversion to methane, methanol, and ammonia. Use of an essentially pure mixture of hydrogen and carbon monoxide, admittedly a far less expensive approach, would result in meaningless data because of unknown effects of impurities. The study of the synthesis can be carried out on a benchscale or small pilot plant level since scaling effects from such research are well established.

Similar to the above synthesis research is the activity devoted to chemical modification of the waste material and its decomposition products prior to isolation of a syngas. Many of the reactions taking place are the same as would occur in the post-treatment mode, but the concept here is to use chemical reagents to directly yield new gaseous or liquid fuel mixtures from solid cellulose. Such work is typified by the BuMines research on solid waste conversion (with CO and/or H_2) at moderately high temperatures and pressures. While low process costs have yet to be demonstrated in the limited laboratory work conducted by several organizations, because of the versatility inherent in this synthesis concept, particularly the potential for making valuable liquid products, support of additional work is warranted. This R&D should consist of further small batch autoclave experiments to learn more about process variables, followed by scale-up, perhaps at the ERDA Albany, Oregon facility, to a continuous reactor capable of processing several hundred pounds an hour.

It is assumed that EPA will play a continuing role in R&D for overall improved pollution control technology and that research need not be specified here for assuring that superior equipment and processes become available. The increasing requirement for the combustion of coal alone will cause R&D to continue at a significant rate. In very few cases does waste processing create emissions that might not prove controllable through developments needed by other industries. In one case, additional testing is recommended to ascertain if the alkaline ash from wastes tends to chemically absorb sulfur oxides and if any undesirable properties result from mixed coal and waste ash. In another area somewhat unique to waste processing, tests should be made to assure that pathogenic dusts can be adequately removed by the fume hoods and fabric filters now being specified.

Although the great difficulty in applying generalized data to specific needs is widely recognized, some decision-making bodies too often ignore this problem. Additional information on the options available and key operating characteristics of systems can be found in selected documentation. However, local/regional studies and analyses must be conducted before construction of a waste-to-energy processing plant is seriously considered. To rank the candidate systems covered in this report on the basis of national average parameters is meaningless for local planning. Any group wanting to determine the feasibility of incorporating an energy/material recovery facility into its waste management plans must first ascertain whether its own staff is qualified to perform the necessary analysis, and, if it is not, should retain an experienced consulting organization.

With biological energy conversion systems, fuels (methane and alcohols in particular) can be obtained from high water content wastes without the need for energy-consuming drying processes. Economically successful anaerobic digestion operations to date have typically employed "free" labor, have used designs and materials of construction unacceptable to industrialized nations, and have been used where small quantities of fuel gas are required as an alternative to very high price energy forms. Continuing increases in natural gas prices and the important advantages of gaseous fuels will result in some limited methane generation applications on U.S. farms. Support will be needed for final design and demonstration testing of equipment best suited for this purpose. The feasibility of large-scale anaerobic digestion of wastes will be better understood after completion of tests at Pompano Beach (MSW) and at the Oklahoma plant of Thermonetics, Inc. (animal wastes). Present analysis indicates that a rather high drop charge is required to offer the methane at competitive prices and that disposal of the final sludge can present problems. In mid-1978 a definitive report on the practicality of commercial methane production by anaerobic digestion could be prepared. This document should summarize the past and current laboratory work and present engineering conclusions on production facilities in operation at the time.

For many years investigators of hydrolysis/fermentation of cellulosic wastes have believed that their particular process would result in competitively priced fuel-grade ethanol. Only in rare cases, where waste disposal costs are extremely high, has production of alcohol proven economically feasible. Because of the large amounts of agricultural wastes in the U.S. and the ready application of alcohol as a fuel for vehicles and gas turbines, it is recommended that a low level of fermentation research be maintained should a significant technological advance occur.

Coal has been used as an industrial fuel for more than one hundred years and yet research on improved means to efficiently release and use its energy continues at a high level. Although the high rate of improvement experienced with coal in the last 50 years cannot be expected with waste-derived fuels, it appears that much will be learned about superior combustion of such fuels in the near future. Recommended areas of combustion research for waste-derived fuels are listed and described below:

- Conduct detailed experiments at new facilities such as those at Ames, Saugus, and Chicago. Make measurements on gas and ash compositions, deposition of slag and soot, corrosion and erosion of steam generating tubes, and observations of flame characteristics.
- Through adaptation of an existing RDF-fired furnace or construction of special R&D equipment, study effects of injection port geometry, size, and location; injection air-to-RDF ratio; and varying compositions of coal and waste.
- Establish the best means to use solid waste-derived fuels as a heat source for existing oil and gas-fired furnaces. (Note: This need not imply that the solid fuel must be burned within the present furnace; external heat recovery systems should be considered.)
- Continue R&D to improve grate-supported (mass burning) combustion systems. The inherent simplicity of these systems offers a significant advantage, but they still experience problems of incomplete burn-out, corrosion, erosion, and nonsteady steam generation.
- Conduct R&D on small energy-recovery incineration to minimize problems of automatic feed, high maintenance, and excessive emissions. This would permit profitable use in major commercial and high density housing projects.

WASTE MATERIAL UTILIZATION

The principal conclusions to be drawn regarding U.S. waste materials are that (1) the total quantity (and heating value) is impressively large, and (2) the fraction considered economically available for energy purposes cannot yet be accurately defined. Present survey information on total national waste quantities is sufficiently accurate for most purposes. Studies have revealed that several of the methods popularly employed for estimating availability can lead to erroneous values. With one method, usually applied by workers still conducting basic laboratory research, a statement is made such as "the very conservative assumption has been used that only 50 percent of the total agricultural wastes will actually be available." This phrasing has led some literature reviewers to believe the assumption is truly conservative, when actually it has no factual basis. Another estimating method assumes all construction of processing facilities in proportion to the metropolitan population. This method does not take into account the costs of local alternative disposal, the need for particular types of energy forms, financing abilities, or specific environmental pollution problems. Again, the fraction to be employed is ill-defined.

While the percentage of total energy needs that could be supplied by U.S. wastes is highly speculative, even a cursory analysis leads to the conclusion that futher development of conversion systems should be encouraged. If only 2 percent (a reasonable amount from existing information) of anticipated 1980 energy needs were supplied, this would amount to an annual value of $4.38 billion.

Additional waste quantification at the local and regional level is needed by governments and organizations considering incorporation of resource recovery facilities into their waste management systems. Specific local studies must be conducted on current and projected quantities and compositions of waste throughout the year, transportation costs, and the nature of the markets for materials and fuels. Analyses should be continued on the technological and economic factors affecting the availability of wastes for conversion to energy forms. Availability of agricultural (farm, logging, and feedlot operations) wastes are most difficult to determine and prime attention should be directed to this area. In addition to analytical studies of collection and transportation costs and the best means of utilizing the energy contained in these wastes, experiments should be conducted on the efficiency of equipment to gather agricultural wastes and the long-term effect of removing these materials from their normal place of generation.

Parsons has examined a number of samples of pelletized agricultural wastes of excellent mechanical integrity, with heating values 50 to 100 percent higher than the original waste because of water loss and chemical modifications during the pressing operations. This approach yields a fuel having a higher boiler efficiency than the original wet waste and which would minimize transportation costs to a user. Further R&D on the densification of agricultural wastes and characterization of physical and combustion properties is recommended.

Waste materials are primarily cellulosic in nature. Essentially all considerations for obtaining useful energy from these wastes ultimately use total oxidation of the carbon and hydrogen (whether directly or through burning of pyrolytic syngas or anaerobically formed methane). Analysis should be directed toward chemical synthesis from cellulose. Such a process might be more attractive than combustion from an overall energy standpoint.

Materials recovery is outside the scope of this report. However, it is impossible to ignore the importance of this area as the required sales price of energy forms is a function of the total resource recovery plant economics. R&D of superior materials recovery processes is essential and should be fully coordinated with waste-to-energy conversion activities.

GLOSSARY AND ABBREVIATIONS

ACFM: Actual cubic feet per minute (as opposed to mathematical correction to a standard temperature and pressure)

Anaerobic digestion: Conversion of organic material through the action of natural micro-organisms in the absence of air; methane is the product of interest for energy consideration.

BOD: Biochemical Oxygen Demand; a standardized biological method of measuring the quantity of organic contaminants in water capable of consuming oxygen.

CFM: Cubic feet per minute

COD: Chemical Oxygen Demand; a standardized chemical oxidation method of measuring the quantity of organic contaminants in water capable of consuming oxygen.

DCS: Dry combustible solid

dm^3: Cubic decimetre, the SI term for the former metric liter; see SI explanation in Appendix E.

EES: Engineering Experiment Station of Georgia Institute of Technology

Fossil fuel: Fuels naturally formed over extensive time periods by the "fossilization" of large organic (plant) deposits; includes the various coal grades, petroleum-derived liquid fuels, and natural gas.

GPD: Gallons per day

GPM: Gallons per minute

HHV: Higher heating value; the heat released upon complete oxidation (combustion), including the heat of condensation of water vapor.

Hogged fuel: Chopped or shredded wood or other fibrous fuel

IR&T: International Research and Technology Corporation

LHV: Lower heating value; the heat released upon complete oxidation (combustion), not including the heat of condensation of water vapor. Most European work is in terms of LHV.

Mass burning: As opposed to "suspension" burning, the fuel combustion occurs on any of several types of support grates, typically moving.

Mg: Megagram (one million grams or one thousand kilograms), the SI expression for the former metric tonne (2204.6 lb); see SI explanation in Appendix E.

MJ: Megajoule, a million joules of energy, equivalent to 947.8 Btu; see SI explanation in Appendix E.

MRI: Midwest Research Institute

MSW: Municipal solid waste

Nm^3: Normal cubic meter, the standardized SI gas volume (0°C and 1 atm), equal to 37.33 standard cubic feet (60°F and 1 atm). See SI explanation in Appendix E.

ORC: Occidental Research Corporation

Pa: Pascal, the SI unit of pressure; 1 psi equals 6 895 Pa. See SI explanation in Appendix E.

Pyrolysis: Thermal decomposition of organic materials in the absence or near absence of gaseous oxygen.

RDF: Refuse-derived fuel

RESCO: Refuse Energy System Co., owner-operator of the combustion system at Saugus, Massachusetts

SCFM: Standard (60°F, 1 atm) cubic feet per minute

SI: le Système International d'Unités (modernized metric); see Appendix E for explanation of specific units and format

SNG: Synthetic natural gas

Supplementary fuel: Fuel, typically derived from wastes, used to supplement some fraction of fossil fuel in a furnace.

SWARU: Solid Waste Reduction Unit, Hamilton, Ontario, Canada

Syngas: Synthesis gas, a mixture of hydrogen, carbon monoxide, light hydrocarbons, and carbon dioxide

THERMAL: Nashville Thermal Transfer Corporation

TJ: Terajoule, a trillion (10^{12}) joules of energy, equivalent to 947.8 million Btu; See SI explanation in Appendix E.

TPD: Tons per day

TPH: Tons per hour

TPY: Tons per year

Waterwall boiler: A steam generator in which the combustion zone and hot gas passes are surrounded by structural walls consisting of a large number of pipes filled with flowing water absorbing the heat; fossil or waste fuels may be used.

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APPENDIX A

WASTES IN THE UNITED STATES

INTRODUCTION AND SUMMARY

An appreciation of what wastes there are, their economic availability, heat content, and other characteristics is essential to the planning or evaluation of waste-to-energy facilities. To provide an introductory understanding, national data based on a literature review and comments by experts are summarized and discussed in this section. None of these numbers were originated by The Ralph M. Parsons Company, although data manipulations were made to permit comparisons. These figures should not be used as the basis for designing specific facilities because national averages may bear no relationship to local conditions. Instead, this data should be regarded as a general introduction to waste quantities and characteristics that will establish a foundation for the waste-to-energy process evaluations that follow.

Although data on wastes have been collected for many years, the early definitions of wastes and the measurement techniques were poor, leading to quantity figures of low accuracy. With the present need to find alternatives to landfills, and aided by modern data collection techniques, recent investigators have compiled data that are greatly improved, and these newer figures are used throughout this report.

An attempt has been made to state waste quantities here in terms of dry, combustible, weights available for potential conversion to energy. Data on municipal solid waste, however, are historically given as total collected weight, including moisture and non-combustibles. Where comparisons are being made with other waste quantities, both methods of specifying the quantity of municipal solid waste will be used. The subject of detailed technical and economic availability is one that must be evaluated on a local basis, balancing the cost of collecting and transporting the waste against the revenue from its use.

The three types of waste discussed in this chapter are municipal, industrial, and agricultural. A fourth major type of waste, that from mining operations, is outside the scope of this study. Tabular presentations of the data, along with the information source, are made in the sections dealing with the detailed information on each waste category that follow the summary narrative below.

Municipal Wastes

The two components of municipal waste are municipal solid waste (MSW) and sewage.

MSW includes household waste, commercial and institutional waste, and city street sweepings and prunings. It has been estimated by Smith (Ref. A-1) that in 1971, 1.50 kg per capita per day (3.31 lb/c/d) were collected, totalling 113.4 x 10^6 Mg (125 million tons) per year, including moisture and incombustibles. About one-fourth of that weight is natural moisture, and approximately another fourth is glass, metal, and other incombustibles. The available, dry, combustible weight of municipal solid waste was therefore 61.1 x 10^6 Mg (67.4 x 10^6 tons) in 1971. Paper is the most common material in MSW, with yard and food wastes a distant second and third.

The total weight of MSW, including moisture, metal, and glass, is forecast by Midwest Research Institute (MRI) (Ref. A-2) to grow from 113.4 x 10^6 Mg/y (125 x 10^6 TPY) in 1971, to 144.4 x 10^6 Mg/y (159.2 x 10^6 TPY) in 1980, and 182.2 x 10^6 Mg/y (200.8 x 10^6 TPY) in 1990. The corresponding quantities of dry, combustible MSW are 79.9 x 10^6 Mg/y (88.1 x 10^6 TPY in 1980 and 105.6 x 10^6 Mg/y (116.4 x 10^6 TPY) in 1990.

The average amount of energy contained in raw MSW is estimated to be 10.47 MJ/kg (4500 Btu/lb), sufficiently high to permit unprocessed waste to be used as a fuel. When a portion of the moisture and incombustibles is removed in presently available equipment, the heating value of the combustible fraction isolated is in the range of 13.72 to 14.42 MJ/kg (5900 to 6200 Btu/lb). MRI, in testing 97 samples at the St. Louis-Union Electric project, found the average as-received heating value to be 10.64 MJ/kg (4573 Btu/lb), the moisture-free value to be 14.49 MJ/kg (6231 Btu/lb), and the moisture and ash-free value to be 20.57 MJ/kg (8843 Btu/lb). Depending on the process used, more energy may be consumed making dry, combustible solid waste than can be justified on the basis of the more convenient fuel prepared.

The heating value of municipal solid waste is expected to increase, primarily due to an increase in the use of plastics.

Sewage sludge, the second component of municipal waste, contains human and food wastes, residuals from wash water, and in many areas, treated and untreated industrial wastes. Generation rates of sewage sludge are rising due to increased disposal of food and other wastes in sewage, and to legislation requiring more thorough sewage treatment, which adds inorganics to the waste water. It has been reported by International Research & Technology (IR&T) (Ref. A-3) that there were, on a dry basis, 11.5 x 10^6 Mg/y (12.7 x 10^6 TPY) of sludge in 1970. They estimate this quantity will increase to 14.0 x 10^6 Mg/y (15.4 x 10^6 TPY) in 1980 and 14.0 x 10^6 Mg/y (18.2 x 10^6 TPY) in 1990. Not all of this is combustible, because it contains some dirt and treatment chemicals. Dry sewage sludge has a high heating value, but in its usual state it has such a high water content that it cannot be burned alone. Other processes for obtaining a fuel gas from sewage sludge are discussed later in this report.

Industrial Wastes

Industrial wastes, including processing wastes and plant trash, was estimated to total 93.4 x 10^6 Mg/y (103 x 10^6 TPY) in 1965. Less than half of that, about 41.7 x 10^6 Mg/y (46 x 10^6 TPY) was dry, combustible, solid (DCS) waste. The wood, paper, and allied industries produced the greatest quantity of process waste, but they are also very active in seeking ways to avoid or utilize these wastes. The construction and demolition industries are the next major producers of process wastes. These two industrial groupings were estimated to produce 88% of the DCS process waste in 1967, or 54% of DCS industrial waste including plant trash.

Total DCS industrial wastes are forecast to grow slowly, from 42.3 x 10^6 Mg/y (46.6 x 10^6 TPY) in 1967, to 48.2 x 10^6 Mg/y (53.1 x 10^6 TPY) in 1980, and 50.0 x 10^6 Mg/y (55.0 x 10^6 TPY) in 1990. A decline in wood and paper industries wastes is expected to be offset by an increase in plant trash, chiefly wooden shipping cases, cardboard, and paper.

The average heating value of DCS industrial waste has been estimated to be 20.88 MJ/kg (8976 Btu/lb).

There are also gaseous and liquid industrial wastes. One estimate puts the total quantity of wet waste liquids and sludges at 15.4 x 10^6 Mg (16.98 x 10^6 ton) in 1970, mostly from the chemical and machinery industries. No reference was found on the total quantity of gaseous industrial wastes.

Agricultural Wastes

Agricultural wastes include crop, livestock, and forestry wastes, all of which are candidates for some form of conversion to energy. The highest estimate of the wet-basis quantity of agricultural wastes is a total of 1941 x 10^6 Mg/y (2140 x 10^6 TPY) for 1966 (Ref. A-4). Livestock wastes accounted for 73 percent of the total in this estimate; crop wastes accounted for most of the remainder. Many of these wastes are scattered, livestock manures in particular, so that they are not readily available for energy conversion. Estimates of the dry, available, wastes in 1970 range from 210.2 x 10^6 (Ref. A-3) to 585 x 10^6 (Ref. A-5) Mg/y (231.7 x 10^6 to 645 x 10^6 TPY). Based on the lower figure, these are forecast (Ref. A-3) to grow to 316.2 x 10^6 Mg/y (348.5 x 10^6 TPY) in 1980 and 385 x 10^6 Mg/y (424 x 10^6 TPY) in 1990 (available DCS wastes).

Heating values of DCS agricultural wastes range from 13.96 to 19.42 MJ/kg (6000 to 8350 Btu/lb).

Total Wastes

The total dry combustible wastes, summed from the data given in the preceding paragraphs, is shown in Table A-1. The annual combustible waste

TABLE A-1. TOTAL WASTE QUANTITIES IN THE UNITED STATES

	Dry Combustible Waste (From Various Sources Compiled in this Report)						Eliassen (Ref. A-4) Wet Total Wastes		EPA First Report to Congress (Ref. A-6) Wet Total Wastes		IR&T (Ref. A-3) Dry Combustible	
Year	Early 1970's		1980		1990		1967		1971		1967 - 1970	
	SI*	Eng.*	SI	Eng.	SI	Eng.	SI	Eng.	SI	Eng.	SI	Eng.
Waste Stream												
Municipal												
Municipal Solid Waste	61.1	67.4	78.0	86.0	98.0	108.0	232.2	256	209	230	103.6	114.2
Sewage Sludge	11.5	12.7	14.0	15.4	16.5	18.2	-		-		11.5	12.7
Industrial	42.3	46.6	48.2	53.1	49.9	55.0	99.8	110	127	140	41.2	45.4
Agricultural	210.2	231.7	316.2	348.5	384.6	424.0	1919	2115	2159	2380	212.3	234.0
TOTAL	325.1	358.4	456.3	503.0	549.0	605.2	2251	2481	2495	2750	368.6	406.3

*SI units throughout are Tg/y and English are in millions of tons per year.

generation rate is expected to increase by 40% between 1970 and 1980, and by 20% between 1980 and 1990. This declining change in the waste generation rate is expected because of current efforts to reduce industrial and agricultural waste generation, and to find uses for those wastes that are generated, thus removing them from the waste category.

For comparison, the results of some earlier estimates are also shown. Rolf Eliassen (Ref. A-4), in a report prepared for the Executive Office of the President, made an estimate of the total quantity of waste based on very limited data. The estimate overstates the quantities of wastes because some of the factors used were unmeasured estimates, moisture is included, and the agricultural quantity is based on the total number of animals, not just those whose wastes are concentrated. The EPA's First Report to Congress (Ref. A-6) essentially factored up Eliassen's numbers from 1967 to 1971, with some modifications where newer information had cast doubt on the earlier numbers. International Research and Technology (Ref. A-3) used these and other earlier estimates, but cross-checked and refined them by making an analysis covering each step of the production and consumption process. They were also the first to give their estimates in terms of totally dry weights. In some respects this can be misleading, because the weight of wastes that must be handled include moisture. However, the moisture content varies so much between waste types that the estimates of the total quantity are more distorted by considering the wastes with moisture than by considering them dry.

Some of the early estimates, particularly Eliassen's and Anderson's (Ref. A-5), were widely quoted and used inappropriately. Care should be taken when considering the quantities of wastes to use the most recent estimates. The older the estimate, the more likely it is to have a large, inflationary "guess" factor.

MUNICIPAL WASTES

Classification System

More data have been compiled for municipal wastes than for any other major type of waste. These data are usually reported in terms of origin or in terms of composition:

By Origin

Residential - Daily household wastes

Commercial - Waste from stores, business, offices and institutions.

Other Municipal - Municipal street sweepings, tree trimmings, and catch basin residue

By Composition

Paper
Glass
Metals
Plastics
Rubber and Leather
Textiles
Wood
Food Wastes (garbage)
Yard Waste
Miscellaneous (dirt, fines)

These classification systems vary. For example, the "origin" classification may also include bulky household waste such as appliances and furniture, or dewatered sewage sludge. The "composition" classification may group glass, ceramics, and similar inorganics together or may further subdivide the metals. In either case, there can be problems in comparing data from different sources because of these variations. As mentioned previously, the weight of these wastes has historically been given with the moisture content included, and to avoid incompatibilities with other published data that convention will also be followed in this section.

Quantities

The earliest studies of the quantity of municipal solid wastes tended to use the "origin" classification system because it was simple to implement and provided useful broad planning data. In Table A-2, Combustion Engineering (Ref. A-7) used data developed by the Refuse Removal Journal to arrive at a MSW generation rate of 1.68 kg/capita/d (3.7 lb/capita/d). The National Solid Waste Survey (Ref. A-8) analyzed data from 6,259 communities in developing a figure of 2.41 kg/capita/d (5.32 lb/capita/d). Rolf Eliassen (Ref. A-4) referred to both of these studies and derived a generation rate of 3.18 kg/capita/d (7.0 lb/capita/d). International Research and Technology (Ref. A-3), and Niessen and Chansky (Ref. A-9) also used the National Solid Wastes Survey (Ref. A-7) data in preparing their estimate of dry combustible solid waste, and Roberts et al (Ref. A-10) relied on Niessen and Chansky's work. Thus there are a number of studies using data from one or two early sources, and, while they were the best data available at the time, they were known to have shortcomings (Ref. A-4, A-7, A-10). Much of the quantity data was estimated rather than measured, and the definitions of waste types were not uniform across the country.

Consequently, some revisions were in order. EPA's Frank A. Smith, in an analysis of a large number of national municipal waste estimates, has described (Ref. A-1) some of the factors that led to a change from the early 1967 figures used by the Office of Solid Waste Management Programs (OSWMP) of 2.41 kg/capita/day and 172 x 10^6 Mg/year (5.32 lb/capita/day and 190 million TPY) to the newer 1971 figures of 1.50 kg/capita/day and 113.4 x 10^6 Mg/year

TABLE A-2. MUNICIPAL WASTE GENERATION RATES

		kg/capita/day	lb/capita/day
Combustion Engineering	(Ref. A-7)	1.68	3.7
National Solid Wastes Survey	(Ref. A-8)	2.41	5.32
Rolf Eliassen	(Ref. A-4)	3.18	7.0
Smith	(Ref. A-1)	1.50	3.31

(3.31 lb/capita/day and 125 million TPY). He made three major points. First, the 1968 survey results that provided the basis for the old figures were never fully analyzed. Second, the figure of 2.41 kg/capita/day includes reported demolition, construction, and industrial wastes, in addition to residential, commercial/institutional, and street wastes. The figure for the latter three items from the 1968 data was about 1.92 kg/capita/day (4.24 lb/capita/day). Third, he located two analyses suggesting that the 1968 survey returns tended to overestimate the quantities of collected waste, although the extent of the overestimation is uncertain. One analysis of the results made a comparison between estimated and measured data, indicating that the measured data was consistently lower (Ref. A-11). The second analysis was made by Darnay and Franklin (Ref. A-12), who compared reported wastes collected to consumption data. They found that the quantities of various products consumed were not sufficient to account for the high volume of reported waste collected, but fit reasonably well if a lower total urban wastes figure was assumed.

The estimates of 1.50 kg/capita/day and 113.4 x 10^6 Mg/year (3.31 lb/capita/day and 125 million TPY) are for the year 1971. U.S. EPA's "Third Report to Congress: Resource Recovery and Waste Reduction" (Ref. A-13) updated these numbers to 1973, using the same definitions and similar methods of calculation in order to make the two estimates directly comparable. Total post-consumer municipal waste increased to 122.5 x 10^6 Mg (135 million tons), an 8% growth, and per capita generation increased to 1.60 kg/d (3.52 lb/day), a 6.3% growth. However, there is a warning that these growth rates should not be used for making forecasts because 1971 was not a very strong year for many products, whereas 1973 was generally a boom year by comparison.

It is Parsons' conclusion that further refinement of national statistics of waste quantities will not significantly assist in planning for the disposal of the wastes or their conversion to energy. There is a large variation in waste quantities and compositions from city to city, requiring a local analysis of the potential for energy recovery before any final facility design can be accomplished.

Composition

Per capita figures are useful for quickly estimating total quantities of waste generated, but compositional data are much more useful for determining how best to dispose of or utilize the waste. The results of a number of waste composition studies are shown in Table A-3. By far the most quoted of these is "The Nature of Refuse" by W.R. Niessen and S.H. Chansky (Ref. A-9). This project collected and summarized the results of 23 sets of apparently independent sample collection data, and then analyzed them in detail to develop an estimated annual average national refuse composition, shown in Table A-3, Column 3. This estimate excluded yard waste because of seasonal and geographical variation. The Reference A-9 report was updated by Niessen and A.F. Alsobrook in 1972 (Ref. A-14). Smith (Ref. A-1) took an analytical, as opposed to empirical, approach in conducting the materials flow study that resulted in the 1.50 kg/c/d (3.31 pounds per capita per day) figure mentioned earlier. The National Center for Resource Recovery (Ref. A-11) has developed a municipal waste composition based on a material flow analysis, as has also

TABLE A-3. COMPOSITION OF MUNICIPAL WASTE*
Percent by Weight

Columns	1	2	3	4	5	6	7	8	9	10	11
Data Source	APWA	KAISER	NIESSEN & CHANSKY	NIESSEN & CHANSKY	NIESSEN & ALSOBORRK	NCRR	SMITH	SMITH	EPA (SMITH)	EPA (SMITH)	NYC
Reference (A-)	15	16	9**	9	14	11	1	1	13	13	17
Year	1939	1967	1968	1968	1970	1971	1971	1971	1973	1973	1975
Basis***	Collection Data	Collection Data	Collection Data	Adjusted to Material Flows	Adjusted to Material Flows	Materials Flows	Materials Flows	Adjusted to Collection Data	Material Flows	Adjusted to Collection Data	Collection Data
Locality	New York City	Long Island									New York City
Kinds of Materials											
Paper	21.9	42.6	50.7	35.1	37.4	33.2	31.3	37.8	32.8	39.6	52.5
Glass	5.5	9.6	9.7	8.1	9.0	9.4	9.7	10.0	9.9	10.0	8.1
Metals	6.8	8.5	10.0	8.1	8.4	8.6	9.5	10.1	9.3	9.5	7.5
(Ferrous)						7.7	8.5		8.2		
(Aluminum)						0.55	0.6		0.7		
(Other Non-Ferrous)						0.39	0.3		0.3		
Plastics	3.2	4.6	1.4	1.1	1.4	1.9	3.4	3.8	3.7	4.1	3.2
Rubber, Leather			1.9	1.4	1.2	1.4	2.6	2.7	2.6	2.7	0.6
Textiles		3.1	2.6	1.9	2.2	2.5	1.4	1.6	1.4	1.6	0.7
Wood	2.6	3.2	2.9	2.4	3.1	42.9	3.7	3.7	3.6	3.6	0.8
Food Waste (Garbage)	7.0	10.9	19.1	19.5	20.0		17.6	14.2	16.6	13.3	18.1
Yard Waste		17.6	NA	20.7	13.9		19.3	14.6	18.5	14.1	4.9
Miscellaneous	43.0	-	1.7	1.7	3.4		1.4	1.5	1.4	1.5	3.6
	100.0	100.1	100.0	100.0	100.0	99.9	100.0	100.0	100.0	100.0	100.0

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* Includes residential and commercial waste, but original sources are not clear as to whether or not street sweepings, other city waste, or bulky wastes are included. All compositions are on a national basis unless indicated.

** Niessen & Chansky specifically excluded yard waste from this estimate because of its seasonal and geographic variability, causing all the other percentages to be high. Yard waste would amount to 10% to 20% of the total if included.

*** Columns given on a "material flows" or "adjusted to material flows" basis include moisture immediately prior to material discard; those given on a "collection data" or "adjusted to collection data" basis assume moisture transfer among materials in collection and storage, but do not change of moisture for the total.

U.S. EPA (Ref. A-13). These five reports contain the best information available on national average waste composition and characteristics.

Of the eleven compositions shown in Table A-3, the first five and the last one were determined from sample collection data, and six through ten by calculated material flows analysis. Preparing collection data involves handsorting samples of municipal waste and weighing each component. This method gives an accurate picture of the waste composition as it is actually received, which is important when planning waste disposal or resource recovery systems, but the samples must be carefully chosen to fairly represent the seasons of the year and the localities from which the collections are made. Material flows analysis involves calculating from industrial production data the amount of each material that enters the waste stream, less the amount recycled, to arrive at the net waste for disposal. This approach is much more useful for determining national averages than is the method using physical sampling, which essentially yields a series of spot measurements. However, it requires estimates of the time interval between production and discarding for each material, as well as the amount recycled. In addition, there is no way to estimate food waste, yard waste, or miscellaneous waste by material flows analysis; these must be determined from sample collection data and added in.

Moisture Content

There is one other important difference between compositions of waste calculated on material flows and on a collection data basis, and that is moisture content. Flows analysis provides an estimate of waste on an "as-generated" basis, so that the percentage moisture it contains is the percent that was there at the time immediately prior to disposal. As it is discarded and mixed with other wastes, a material may gain or lose moisture. Collection data provide a measurement of waste on an "as-disposed" basis, after this moisture transfer has taken place. The "as-disposed" figures are to be used for designing a resource recovery facility, where it is important to know the characteristics of the materials to be handled. They are not useful for estimating future quantities of waste, since these projections are based on paper produced that has a different moisture content. Therefore, the waste compositions determined from flows analysis or collection data may have to be adjusted for moisture content, depending on the final use of the data.

Niessen and Chansky (Ref. A-9) give the following information on moisture content:

	Weight Percent Moisture	
Kinds of Material	Materials Flows Basis "As Generated"	Collection Data Basis "As Disposed"
Paper	8.0	24.3
Glass	2.0	3.0
Metal	2.0	6.6

Kinds of Material	Weight Percent Moisture Materials Flows Basis "As Generated"	 Collection Data Basis "As Disposed"
Plastics	2.0	13.8
Rubber, leather	2.0	13.8
Textiles	10.0	23.8
Wood	15.0	15.4
Food Waste	70.0	63.6
Yard Waste	50.0	37.9
Miscellaneous	2.0	3.0

These factors have been widely used to adjust between flows and collection data analyses; all of the "adjusted" data in Table A-3 have been developed on this basis.

The moisture content of mixed municipal solid waste can vary greatly. In five samplings of refuse collected from Long Island households during a period when no rain fell, Kaiser (Ref. A-16) found the moisture content to range between 19% and 42%. The high moisture content refuse was collected on a Monday morning in June, following a cool, humid period, and contained grass and leaves from lawn care. A moisture content of 26% was found in refuse collected on a Friday in February. The residential sources were in the heating season, and Kaiser comments that this would cause a low moisture content in the waste paper (Ref. A-16).

The annual average moisture content of refuse was reported by Kaiser (Ref. A-16) to be 28.3%; by Niessen and Chansky (Ref. A-9) to be 28.3%; and by Snyder (Ref. A-18) to be 25.1%.

Factors Influencing the Characteristics of Municipal Waste

A review of Table A-3 highlights some interesting statistics. The first and last columns show a long term trend for New York City, indicating the decline of ash and the rise of paper as major components of municipal refuse. New York City is a densely populated area, however, having a higher percentage of paper waste and a lower percentage of yard waste than the national average. With the exception of Kaiser's Long Island study, the remaining eight compositional estimates are national averages, arranged in chronological order from left to right and covering a period from 1968 through 1973. Given the different sources and methods of calculation for these estimates, they are surprisingly uniform, with no strongly apparent trends. In fact, removing the ash content from the 1939 New York City estimate shown in Column 1 of Table A-3 brings the paper content up to 38.4%, the glass up to 9.6%, and the metals up to 11.9%, quite in line with current estimates. These figures are percentages, and give absolutely no indication of the total quantity of waste. Data developed by the Public Health Service (reported in Ref. A-15) indicates that total refuse production in the United States was estimated to be 70 million tons per year in 1940 and 190 million tons per year in 1970, agreeing closely with the figures from the National Solid Waste Survey (Ref. A-8), which were developed under similar assumptions. Therefore, even though the adjusted percentage composition has remained relatively stable, the quantity has increased by more than 170%, or 3.4% per year. Approximately half of this increase can be attributed to the total population increase and half to the per capita increase in the amount of refuse generated.

The original sources of the materials found in municipal waste have been investigated by several researchers (Ref. A-1, A-11 and A-13). Table A-4, from U.S. EPA's "Third Report to Congress" (Ref. A-13) shows such a material flow analysis. From this table it can be seen that the paper for containers and packaging is the largest single contributor to total product waste, with food waste (garbage) second, and glass containers third. Yard waste, the largest single contributor to the total municipal waste stream, is outside the product waste flow.

A number of cyclical variations in waste generation can be identified, including weekly, yearly, and seasonal. Collections following a weekend may have above average quantities of yard waste and collections following Christmas, unusual quantities of packaging materials. Any program for collecting data on waste quantities must take these cyclical patterns into consideration. This is especially important when discussing yard waste, which is a large and highly variable component of municipal solid waste. Niessen and Chansky (Ref. A-9) found a significant annual variation in yard waste and attributed it to seasonal climatic changes. In regions with little seasonal change, yard waste is generated all year, and is a larger contributor to municipal waste than in regions of greater seasonal change where the growing season is less. Based on limited sample collection data, the seasonal variations in percent yard waste they found are:

	Summer	Fall	Winter	Spring
Northern States	22.9%	6.4%	0.3%	11.1%
Southern States	22.5%	5.2%	6.8%	9.2%

Naturally, in densely populated urban areas or in areas with unusual climatological conditions these averages may not be at all representative; New York City (Col. II of Table A-4) for example, shows only 4.9% yard waste.

If these figures were stated on a materials flow basis, they would be 30% to 45% higher, because yard waste loses a significant amount of moisture between the time it is generated and the time it is disposed of. Note that these figures have been developed from limited data, and that regional and other differences may also have a large, undetermined effect.

TABLE A-4. MATERIAL FLOW ESTIMATES OF RESIDENTIAL AND COMMERCIAL POST-CONSUMER NET SOLID WASTE DISPOSED OF, BY MATERIAL AND PRODUCT CATEGORIES, 1973*†

Material	Product category (In millions of tons, as generated)‡							Totals			
								As-generated weight‡		As-disposed weight§	
	Newspapers, books, magazines	Containers, packaging	Major household appliances	Furniture, furnishings	Clothing, footwear	Food products	Other products	Million tons	Percent	Million tons	Percent
Paper	11.3	23.3	-	tr.	tr.	-	9.6	44.2	32.8	53.4	39.6
Glass	-	12.1	tr.	tr.	-	-	1.1	13.2	9.9	13.4	10.3
Metals	-	6.5	1.9	0.1	tr.	-	4.0	12.5	9.3	12.7	9.9
Ferrous	-	5.6	1.7	tr.	-	-	3.7	11.0	8.2		
Aluminum	-	0.8	0.1	tr.	-	-	0.1	1.0	0.7		
Other nonferrous	-	0.1	0.1	tr.	-	-	0.2	0.4	0.3		
Plastics	tr.	3.1	0.1	0.1	0.2	-	1.6	5.0	3.7	5.6	4.1
Rubber and leather	-	tr.	-	tr.	0.5	-	3.0	3.6	2.7	3.7	2.7
Textiles	tr.	tr.	-	0.6	0.6	-	0.7	1.9	1.4	2.1	1.6
Wood	-	1.9	-	2.5	tr.	-	0.5	4.9	3.6	4.9	3.6
Total nonfood product waste	11.3	46.9	2.1	3.4	1.3		20.5	85.4	63.5	96.0	71.1
Food waste	-	-	-	-	-	22.4	-	22.4	16.6	18.0	13.3
Total product waste	11.3	46.9	2.1	3.4	1.3	22.4	20.5	107.8	80.1	114.0	84.4
Yard waste								25.0	18.5	19.0	14.1
Misc. inorganics								1.9	1.4	2.0	1.5
Total								134.8	100.0	134.8	100.0

*Smith, F.A., and F.L. Smith, Office of Solid Waste Management Programs, Resource Recovery Division. Data revised Dec. 1974.

†Net solid waste disposal defined as net residual material after accounting for recycled materials diverted from waste stream.

‡"As-generated" weight basis refers to an assumed moisture content of material in its final use prior to discard, for example: paper at an "air-dry" 7 percent moisture; glass and metals at zero percent.

§"As-disposed" basis assumes moisture transfer among materials in collection and storage, but no net addition or loss of moisture for the aggregate of materials. Based on estimates in Ref. A-9.

The influence of demographic factors on the generation of residential solid waste has been investigated by the Los Angeles Bureau of Sanitation (Ref. A-19), R. G. Davidson (Ref. A-20), and C. R. Rhyner (Ref. A-21). The Los Angeles study found that the type of dwelling was the most important factor. The average single family house generates 2.5 to 3 times as much refuse as the average apartment in a multiple dwelling complex, including yard waste. Rhyner's study, which covered six southern states plus a portion of Wisconsin, was unable to form any conclusion on the difference in generation rates between single family dwellings and apartments because of the influence of other factors. Rhyner's study excluded yard waste, which was called the major contributor to seasonal and geographic variations in the amounts of domestic solid waste, because of its variability.

Davidson and Rhyner both found that the total amount of domestic solid waste generated per family could be expressed as an amount per family plus an amount per family member. Paper, organic garbage, and metal increase the most with increasing household size, while newspapers, plastics, and colored glass increase the least, according to Rhyner.

Solid waste generation also varies with affluence, as measured by the size of the dwelling and ownership of air conditioning. Rhyner found that the more affluent households tended to generate more paper and more total waste. The Los Angeles study, however, found variations in waste generation due to economic level, but the impact was small and the pattern insufficiently clear to permit generalizations.

The amount of solid waste generated by farm households is significantly less than that generated by urban households, according to Rhyner. In both the southern states and in Wisconsin he found that farm households generated significantly less paper and glass than urban households. In Wisconsin, farm households produced 20% less total waste, and in the South, about 12% less. In both surveys the number of people in the household account for about a 6% difference (Ref. A-22).

Ultimate Analysis

An ultimate analysis for typical mixed municipal solid waste given by Snyder (Ref. A-18) is shown in Table A-5; Kaiser (Ref. A-16) has made a similar analysis. Two appealing characteristics encouraging the use of refuse as a fuel can be seen: the low sulfur and the relatively low chlorine percentages. Roberts (Ref. A-10) has pointed out that U.S. municipal solid waste has a consistent average sulfur content of 0.1% to 0.2%, in contrast to the 2.5% to 3.5% for typical power plant coals. The chlorine content of refuse is in the high end of the range for coals now burned (Ref. A-10), but tests at St. Louis (Ref. A-23) with air classified shredded combustibles showed that two-thirds of the chlorine is in the form of inorganic chlorides that normally would not react in a furnace to form HCl. Further experience is required to establish the quantity of chlorides that will be present in stack gases. Analysis of refuse in Chicago showed that more chlorine originates in the rubber (chlorinated elastomers) than in the plastics fraction (polyvinyl chloride) (Ref. A-18).

TABLE A-5. ULTIMATE ANALYSIS AND HEATING VALUE FOR TYPICAL MIXED MUNICIPAL SOLID WASTE

Component	Analysis (as received) % by weight	Analysis (Dry Bases) % by weight
Moisture	25.1	0.0
Carbon	25.2	33.5
Hydrogen	3.2	4.3
Oxygen	18.8	25.2
Nitrogen	0.4	0.5
Chlorine (organic 0.16), (inorganic 0.14)	0.3	0.4
Sulfur	0.1	0.1
Metal	8.7	11.6
Glass, ceramics	12.2	16.3
Ash	6.0	8.1
Total	100.0	100.0
Higher heating value, HHV	4,400 Btu/lb	5,600 Btu/lb

Source: Ref. A-18

Snyder (Ref. A-18) comments that the carbon content of the combustibles is low with respect to usual commercial fuels because of the cellulosic character of the combustibles, where half the weight is in oxygen. Such items as rubber and plastics contain little or no oxygen and are high in carbon and hydrogen. Dry paper has an HHV of approximately 18.61 to 20.24 MJ/kg (8,000 to 8,700 Btu/lb), rubber and leather have values in the 17.44 to 29.77 MJ/kg (7,500 to 12,800 Btu/lb) range, and plastics are in the 37.22 to 41.87 MJ/kg (16,000 to 18,000 Btu/lb) range (Ref. A-18).

The energy content per unit weight depends on the quantity and chemical characteristics of the individual components, and the amount of moisture present. Snyder (Ref. A-18) gives a value of 19.31 MJ/kg (8300 Btu/lb) for the dry, organic portion of municipal solid waste. The addition of inorganics, which have very low heating values, and water, which has no heating value, reduces the heating value down to the range of 10.12 to 10.70 MJ/kg (4350 to 4600 Btu/lb) (Refs. A-9, A-18, A-2, A-24).

Forecasts of Municipal Waste

Four independent forecasts of municipal waste have been identified: Niessen and Chansky (Ref. A-9); Roberts et al (Ref. A-10); International Research and Technology (Ref. A-3); and Midwest Research Institute (MRI) (Ref. A-2). Table A-6 summarizes the results of these projections. The Niessen and Chansky, the Roberts and the IR&T estimates are now outdated by the MRI projection, but interesting comparisons can be made.

The Niessen-Chansky projections were made by developing national growth rate indicators for each of the 10 major categories comprising municipal refuse, and applying these growth rates to a base pound per capita per day waste generation figure determined by material analysis. Data were extremely limited; the base generation figure came from an analysis of one state. In addition, the optimistic growth projections of the late 1960s gave an average growth rate, 1970 - 1990, of 1.8% per year. The resulting waste generation figure for 1990 of 366×10^6 Mg (403 million tons) is more than twice the current estimate of 182×10^6 Mg (200.8 million tons).

One important factor that Niessen and Chansky tried to take into account is the difference between generated waste and collected waste. They developed a 1968 national average figure of 69% collected, and allowed it to increase in a linear fashion to 95% in the year 2000 (Ref. A-9). The reasonableness of this assumption is uncertain; it is unknown that a significant percent of municipal waste disappears as litter or is indiscriminately dumped, but the effect of this and how it may change in the future is unknown.

The Roberts estimate (Ref. A-10) assumed a growth rate of 1.5% per year based on the increase in per capita consumption of non-durable goods for the period 1950 to 1967. Since this period included cycles of both economic recession and growth, the authors felt it to be reasonably representative. The base per capita collected rate was determined from the 1968 National Solid Wastes Survey (Ref. A-8), confirmed, interestingly enough, by Niessen's work at A.D. Little on which the Niessen and Chansky estimates (Ref. A-9) are based. The Roberts et al estimate used only the household and commercial figures reported in the National Solid Wastes Survey, but as has been discussed earlier, these figures are the result of over-estimates and have been reduced significantly. Based on the information available at the time, Roberts projected the 1990 quantity of refuse collected to be 282×10^6 Mg (311 million tons), 54% more than the current estimate of 132×10^6 Mg (200.8 million tons) generated.

The IR&T (Ref. A-3) forecasts assumed base levels from the National Solid Wastes Survey (Ref. A-8) and other sources. Analyses were than made to determine the percent of total waste that were dry combustibles in 1970, and how that percentage could be expected to change in 1980 and 1990. The next task was to determine the future per capita generation rate for each category of wastes. In the case of household and municipal wastes this was done in an ad hoc manner since there existed no time series data from which to construct a trend (Ref. A-3). For commercial/institutional waste categories, the generation rate was related to factors such as the number of

Table A-6A. FORECASTS OF MUNICIPAL SOLID WASTES
TOTAL WASTES INCLUDING MOISTURE UNLESS OTHERWISE STATED
(SI Units)

	1970	1971	1975	1980	1985	1990	Average Growth Rate Per Year 1970 - 1990
	Kg Per Capita Per Day						
Niessen & Chansky* (Ref. A-9)							
Generated	2.67	----	3.00	3.35	----	3.84	1.8%
Collected	1.88	----	2.24	2.64	----	3.33	----
Roberts, et al* (Ref. A-10) Collected	2.20	----	2.37	2.55	2.75	2.96	1.5%
IR&T Generated Dry Combustible	1.38	----	----	1.64	----	1.95	----
MRI - Generated	----	1.50	1.58	1.71	1.80	1.91	1.3%
Population (Millions)	204.8	207.0	216.5	230.8	246.2	260.7	
	Tg Per Year						
Niessen & Chansky							
Generated	200	----	237	282	----	366	
Collected	141	----	177	222	----	317	
Roberts, et al* Collected	164	----	187	215	247	282	
IR&T* (Ref. A-3) Generated Dry Combustible	103	----	----	138	----	186	
MRI* - (Ref. A-2) Generated	----	113	125	144	162	182	

*Reported Figures. Other values calculated using population figures shown in MRI report.

Table A-6B. FORECASTS OF MUNICIPAL SOLID WASTES TOTAL WASTES INCLUDING MOISTURE UNLESS OTHERWISE STATED (English Units)

	1970	1971	1975	1980	1985	1990	Average Growth Rate Per Year 1970 - 1990
	Pounds Per Capita Per Day						
Niessen & Chansky* (Ref. A-9) Generated	5.88	----	6.61	7.39	----	8.46	1.8%
Collected	4.15	----	4.94	5.82	----	7.35	----
Roberts, et al* (Ref. A-10) Collected	4.85	----	5.22	5.63	6.06	6.53	1.5%
IR&T Generated Dry Combustible	3.05	----	----	3.61	----	4.30	----
MRI - Generated	----	3.31	3.49	3.78	3.98	4.22	1.3%
Population (Millions)	204.8	207.0	216.5	230.8	246.2	260.7	
	Millions of Tons Per Year						
Niessen & Chansky Generated	220	----	261	311	----	403	
Collected	155	----	195	245	----	350	
Roberts, et al* Collected	181	----	206	237	272	311	
IR&T* (Ref. A-3) Generated Dry Combustible	114	----	----	152	----	205	
MRI* - (Ref. A-2) Generated	----	125	138	159	179	201	

*Reported Figures. Other values calculated using population figures shown in MRI report.

white collar workers, restaurant and retail sales, and the number of school students and hospital patients. Forecasts were made for each factor from data in the Survey of Current Business and the Statistical Abstract of the United States. IR&T included household, municipal, sewage, commercial/institutional, manufacturing plant trash and demolition wastes in their estimate of MSW. For this report, only the household, municipal and commercial/institutional wastes are included in MSW, and IR&T's figures for these wastes are shown in Table A-6. The other wastes are discussed in other sections of this report.

The IR&T data are on a dry, combustible basis and are therefore not compatible with the other forecasts. The household wastes component was assumed to grow at a rate of 2% per year, a very high value, and the combustible portion to increase from 78% in 1970 to 90% in 1990, principally due to an increase in the use of plastics. The increasingly apparent natural gas shortage and escalation in petroleum prices since this forecast was made render these assumptions questionable.

The MRI forecasts (Ref. A-2) have been developed over the past several years for the Office of Solid Waste Management Programs, EPA. They have been quoted in the EPA Reports to Congress (Refs. A-25, A-6, A-13) and elsewhere before being published as Baseline Forecasts of Resource Recovery, 1972 to 1990. The summary table of municipal solid waste generation from that report is shown here as Table A-7. The basis of these solid waste generation values is a calculated forecast tonnage based on EPA's estimate of mixed municipal waste generation and composition for the year 1971, and updating of this data by independent material-by-material forecasts of waste generation made by MRI. EPA's municipal waste generation figure for 1971 was 113.4 x 10^6 Mg (125 million tons) (Ref. A-1); MRI's forecasts produced an average long term growth rate of 1.3% per year for the per capita generation figure. High, medium, and low forecasts were made:

	Low Estimate		Medium Estimate		High Estimate	
	Tg	10^6 Tons	Tg	10^6 Tons	Tg	10^6 Tons
1975	122	135	127	140	130	143
1980	136	150	145	160	154	170
1985	150	165	163	180	181	200
1990	163	180	181	200	218	240

Adjusted for population growth, the high estimate has a long term per capita waste generation growth rate of 2.24% per year, the highest of any of the estimates considered. The low estimate has a long term per capita waste generation growth of 0.71% per year.

An interesting final point can be observed. Some cities are reporting a leveling off in per capita waste generation and if this were to achieve a zero growth rate at, say, the estimated 1975 level of 1.59 kg (3.40 lbs) per

TABLE A-7A. MUNICIPAL SOLID WASTE GENERATION BY MATERIAL CATEGORY, 1971 to 1990
(In Megagrams and Percent)

	1971		1972		1975		1980		1985		1990	
Waste Component	Mg	Percent	Mg	Percent	Mg	Percent	Mg	Percent	Mg	Percent	Mg	Percent
Paper	35.5	31.3	37.6	31.8	38.2	30.6	45.8	31.8	52.0	32.0	61.0	33.5
Glass - containers	10.1	8.9	11.1	9.3	12.2	9.7	13.7	9.5	13.7	8.5	13.8	7.6
other	0.9	0.8	0.9	0.8	1.0	0.8	1.2	0.8	1.4	0.8	1.5	0.8
Total Glass	11.0	9.7	12.0	10.1	13.2	10.5	14.9	10.3	15.1	9.3	15.3	8.4
Ferrous - cans and small items	8.1	7.1	8.4	7.1	9.0	7.2	10.1	7.0	11.3	7.0	12.2	6.7
bulky appliances	1.5	1.3	1.5	1.3	1.5	1.2	1.7	1.2	2.3	1.4	2.4	1.4
other	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.1
Total Ferrous	9.7	8.5	10.0	8.5	10.6	8.5	11.9	8.3	13.8	8.5	14.8	8.2
Nonferrous - packaging Al	0.5	0.5	0.6	0.5	0.9	0.7	1.2	0.8	1.5	0.9	1.8	1.0
other Al	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.1	0.3	0.2	0.3	0.2
Nonferrous - other	0.4	0.3	0.4	0.3	0.4	0.3	0.4	0.3	0.5	0.3	0.6	0.3
Total Nonferrous	1.1	1.0	1.2	1.0	1.5	1.1	1.8	1.2	2.3	1.4	2.7	1.5
Plastics	3.8	3.4	4.1	3.5	5.2	4.1	7.6	5.3	10.0	6.2	12.0	6.6
Rubber/Leather	3.0	2.6	3.1	2.6	3.3	2.7	3.9	2.7	4.5	2.8	5.3	2.9
Textiles	1.6	1.4	1.7	1.5	1.9	1.5	2.2	1.5	2.6	1.6	3.2	1.7
Wood	4.2	3.7	4.3	3.6	4.6	3.7	5.2	3.6	5.9	3.6	6.7	3.7
Sub Total - Manufactured Products	69.9	61.6	74.0	62.6	78.5	62.7	93.3	64.7	106.2	65.4	121.0	66.5
Food Wastes	19.9	17.6	20.2	17.0	20.9	16.7	22.2	15.4	23.8	14.7	25.1	13.8
Yard Wastes	21.9	19.3	22.3	18.9	23.8	19.1	26.6	18.4	29.6	18.3	33.0	18.1
Misc. Inorganics	1.7	1.5	1.8	1.5	1.9	1.5	2.3	1.6	2.6	1.6	3.0	1.6
Total Solid Waste	113.4	100.0	118.3	100.0	125.1	100.0	144.4	100.1	162.2	100.0	182.1	100.0
Total Organics - as generated	89.9	79.3	93.3	78.9	98.0	78.3	113.6	78.6	128.5	79.2	146.2	80.3
Total Inorganics	23.5	20.7	25.0	21.1	27.1	21.7	30.8	21.5	33.7	20.8	35.9	19.7

Sources: Refs. A-2, A-25

TABLE A-7B. MUNICIPAL SOLID WASTE GENERATION BY MATERIAL CATEGORY, 1971 TO 1990
(In Million Tons and Percent)

	1971		1972		1975		1980		1985		1990	
Waste Component	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent
Paper	39.1	31.3	41.5	31.8	42.1	30.6	50.6	31.8	57.3	32.0	67.2	33.5
Glass - containers	11.1	8.9	12.2	9.3	13.4	9.7	15.1	9.5	15.1	8.5	15.2	7.6
other	1.0	0.8	1.0	0.8	1.1	0.8	1.3	0.8	1.5	0.8	1.7	0.8
Total Glass	12.1	9.7	13.2	10.1	14.5	10.5	16.4	10.3	16.6	9.3	16.9	8.4
Ferrous - cans and small items	8.9	7.1	9.3	7.1	9.9	7.2	11.1	7.0	12.5	7.0	13.5	6.7
bulky applicances	1.7	1.3	1.7	1.3	1.7	1.2	1.9	1.2	2.5	1.4	2.7	1.4
other	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.1
Total Ferrous	10.7	8.5	11.1	8.5	11.7	8.5	13.1	8.3	15.2	8.5	16.4	8.2
Nonferrous - packaging Al	0.6	0.5	0.7	0.5	1.0	0.7	1.3	0.8	1.6	0.9	2.0	1.0
other Al	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.1	0.3	0.2	0.3	0.2
Nonferrous - other	0.4	0.3	0.4	0.3	0.4	0.3	0.5	0.3	0.6	0.3	0.7	0.3
Total Nonferrous	1.2	1.0	1.3	1.0	1.6	1.1	2.0	1.2	2.5	1.4	3.0	1.5
Plastics	4.2	3.4	4.5	3.5	5.7	4.1	8.4	5.3	11.0	6.2	13.2	6.6
Rubber/Leather	3.3	2.6	3.4	2.6	3.7	2.7	4.3	2.7	5.0	2.8	5.8	2.9
Textiles	1.8	1.4	1.9	1.5	2.1	1.5	2.4	1.5	2.9	1.6	3.5	1.7
Wood	4.6	3.7	4.7	3.6	5.1	3.7	5.7	3.6	6.5	3.6	7.4	3.7
Sub Total - Manufactured Products	77.0	61.6	81.6	62.6	86.5	62.7	102.9	64.7	117.0	65.4	133.4	66.5
Food Wastes	22.0	17.6	22.2	17.0	23.0	16.7	24.5	15.4	26.2	14.7	27.7	13.8
Yard Wastes	24.1	19.3	24.6	18.9	26.3	19.1	29.3	18.4	32.7	18.3	36.4	18.1
Misc. Inorganics	1.9	1.5	2.0	1.5	2.1	1.5	2.5	1.6	2.9	1.6	3.3	1.6
Total Solid Waste	125.0	100.0	130.4	100.0	137.9	100.0	159.2	100.1	178.8	100.0	200.8	100.0
Total Organics - as generated	99.1	79.3	102.8	78.9	108.0	78.3	125.2	78.6	141.6	79.2	161.2	80.3
Total Inorganics	25.9	20.7	27.6	21.1	29.9	21.7	34.0	21.5	37.2	20.8	39.6	19.7

Sources: Refs. A-2, A-25

person per day, the total quantity of municipal solid waste generated would be influenced by population alone. In that case, the total generated in 1990 would be 151 x 10^6 Mg (166 million tons), only 83% of the current estimate. It is not possible at the present time to say whether there is such a trend independent of economic patterns, but it is interesting to note that, in chronological order, each of the forecasts examined here used a lower base and a lower long term growth rate.

Just as the composition of municipal waste is expected to change over time, the characteristics, specifically the heating value, will also change. The three groups who made the forecasts discussed in the previous section also made the following projections of the heating value in MJ/kg (Btu/lb):

	Niessen & Chansky (Ref. A-9)	Roberts & Wilson (Ref. A-24)	MRI (Ref. A-2)
1970	10.58 (4550)	9.42 (4050)	---- ----
1972	---- ----	--- ----	10.47 (4500)
1975	10.79 (4640)	9.65 (4150)	---- ----
1980	11.00 (4730)	10.00 (4300)	10.82 (4650)
1985	---- ----	10.82 (4650)	11.16 (4800)
1990	11.53 (4956)	12.04 (5175)	11.63 (5000)
Change, 1970-1990	0.94 (406)	2.62 (1125)	1.16 (500)

Many of the municipal refuse components have similar heating values, the notable exception begin plastic and rubber. A large change in the plastic fraction would result in a large change in the average heating value of municipal waste. This is the reason that the Roberts estimate shows such a large change in heating value, but this estimate was made before the 1974 petroleum price increases, which changed the outlook for the plastics industry.

Because the amount of heat per unit time that most energy recovery systems can accept is fixed by their design, the projected increase in heating value can be expected to yield a corresponding decrease in capacity of any given system. For example, a unit designed for a peak of 1000 tons per day of 4500 Btu/lb refuse may have a usable capacity of only 900 tons per day if the heating value of the refuse increased to 5000 Btu/lb.

Sewage

Municipal sewage contains organic and inorganic materials originating as human wastes, garbage, and industrial wastes. A common design figure for domestic (human waste) dry sewage solids is 0.091 kg (0.20 lb) per person per day. Extensive use of garbage grinders in a community will increase this figure substantially (Ref. A-26). Sewage solids generation rates are highly variable; one source reports a range of 0.062 to 0.223 kg (0.137 to 0.491 lb) per person per day (Ref. A-27). These figures will be further increased if industrial sewage is handled by the municipal sewage treatment plant. International Research and Technology (Ref. A-3) uses an average figure for total municipal sewage solids of 0.15 kg (0.34 lb) (dry) per person per day. These solids are present in the sewage in dilute suspension or solutions. By means of various concentrating and water reclamation steps, the solids concentration can be increased to 30% and even higher (Ref. A-2). Until recently, the resulting sludge was frequently landfilled or ocean dumped although it also has some value as a fertilizer (Ref. A-26, A-28). Sludge can also be burned, the dry solids having a heating value of approximately 23.21 MJ/kg (10,000 Btu/lb). However, the high moisture content of the raw sludge reduced this heating value so much that supplementary firing with natural gas or oil is required.

Energy can also be reclaimed from sewage in the form of methane from anaerobic digestion. The Los Angeles Hyperion Sewage Treatment Plant, for example, daily produces approximately 127 426 m^3 (4.5 x 10^6 cubic feet) of a methane-carbon dioxide gas mix having a heating value of 23.63 MJ/m^3 (600 Btu per cubic foot). About two-thirds of this gas is used in the sewage treatment plant to provide power; the other third is piped to a local electric generating station, where it supplies approximately 1% of the energy requirement.

International Research and Technology Corporation (Ref. A-3) projected the generation rate of dry sewage solids to be:

1970	0.15 kg (0.34 lb)/cap/day	11.5 Tg (12.7 x 10^6 tons) per year
1980	0.17 kg (0.37 lb)/cap/day	14.0 Tg (15.4 x 10^6 tons) per year
1990	0.18 kg (0.39 lb)/cap/day	16.5 Tg (18.2 x 10^6 tons) per year

Some authorities believe these quantities to be too high and a more recent estimate by Bernard of the quantity of dry municipal sewage sludge gives much lower annual values (Ref. A-29):

1973	4.3 Tg	(4.7 x 10^6 tons)
1977	4.5 Tg	(5.0 x 10^6 tons)
1985	7.3 Tg	(8.0 x 10^6 tons)
1990	9.1 Tg	(10.0 x 10^6 tons)

The difference between the two estimates can be explained by assuming that Bernard used 0.091 kg (0.20 lb) per person per day versus IR&T's 0.15 kg (0.34 lb). In addition, Bernard appears to have factored the sludge generations rate by the recovery rates for primary and secondary treatment, and by the percentage of the population served by these treatment systems. According to a 1973 report by the EPA (Ref. A-30), 77.6% of the U.S. population is served by public sewerage. Bernard indicates that, of the population served, about 25% are served by primary sewage treatment only, and about 72% by a combination of primary and secondary treatment. Primary treatment can recover 0.054 kg (0.12 lb) per person per day; secondary treatment can recover most of the remaining 0.036 kg (0.08 lb) per person per day of the total 0.091 kg (0.20 lb) per person per day generated (Ref. A-31).

Bernard anticipates a surge in sludge generation due to legislation requiring more extensive treatment (Ref. A-27). Another factor in the per capita increase in sludge generation is an increased standard of living, resulting in greater use of garbage grinders and biodegradable single use materials (Ref. A-32).

INDUSTRIAL WASTES

Types

Industrial wastes can be solid, liquid, gaseous, or sludges. They can be combustible or incombustible, production waste, or plant trash (office, cafeteria, and shipping room waste). However the wastes are defined, they are usually associated with a specific industry by means of the Standard Industrial Classification (SIC) Code (Ref. A-33), and are typically categorized in this manner in compilations and discussions.

The composition of individual industrial process wastes is usually well-known and homogeneous, and because of this they are frequently recycled. Sawmill operations generate large amounts of sawdust, which used to pose a disposal problem. Now much of the sawdust is recycled into particle board, paper pulp, and other products. Combustible industrial gases that used to be vented are now burned to provide process steam. Even natural gas was once a waste in petroleum drilling and processing. The nature of industrial wastes is constantly changing as new uses are found for residual materials and environmental control regulations become more stringent. This means that the industrial waste stream may be growing smaller even though industrial production is expanding, enormously complicating the forecasting process.

Quantities

Data on industrial waste quantities are very limited, particularly on liquid and gaseous wastes. Only three studies were identified as having made an independent, comprehensive assessment of industrial waste quantities. The result of these studies are shown in Table A-8, along with two re-analyses of data from one of them.

The Combustion Engineering Study, reported in Volume II of "Technical-Economic Study of Solid Waste Needs and Practices" (Ref. A-7), includes only solid wastes in 24 SIC Code industry groups, mostly manufacturing. The data was obtained in some 320 interviews, during which an attempt was made to identify office waste and general trash, shipping waste, process wastes, and solid wastes collected by air and liquid cleaning devices. It is not clear, however, whether the data is for dry solids or for solids with normal moisture. The interviews also developed the fraction of total waste utilized in any way, so that the waste quantities reported are those requiring ultimate disposal. Because industrial production data is often regarded as proprietary and is therefore unavailable, the waste quantities were related to the number of employees.

These factors were then multiplied by statistics of industrial employment to calculate the amount of total waste. In the tabulation shown in Table A-8,

TABLE A-8. INDUSTRIAL WASTES IN MILLIONS OF TONS PER YEAR

SIC Code	Description	Combustion Engineering (Ref. A-25) 1965 Solid Waste	Combustion Engineering (Ref. A-25) 1975f Solid Waste	Niessen & Alsobrook (Ref. A-14) 1970 Solid Waste	Niessen & Alsobrook (Ref. A-14) 1970 Liquids & Sludge	International Research & Technology (Ref. A-3) 1967 Dry, Solid Combustible Waste	International Research & Technology (Ref. A-3) 1980f Dry, Solid Combustible Waste	International Research & Technology (Ref. A-3) 1990f Dry, Solid Combustible Waste	Smith (Ref. A-36) 1967 Dry Solid Combustible	Huffman (Ref. A-37) 1970 Dry Solid Combustible
15-16-17	Construction and Demolition	19.05	22.15[a]	-	-	5.15	6.40- 6.58	7.64- 8.02	1.30[b]	3.85
19	Ordnance	0.36	0.44	-	-	-	-	-	Misc.	-
20	Food Products	7.13	9.57	14.17	0.71	0.71	1.10- 1.13	1.21- 1.32	0.71	0.75
21	Tobacco	0.41	0.48	-	-				Misc.	Misc.
22	Textile Mill Products	1.08	1.35	2.11	1.58	0.29	0.48- 0.51	0.61- 0.73	0.29	0.30
23	Apparel	0.36	0.54	2.99	-					
24	Wood Products	38.05	17.92	4.86	-	15.81	12.76-13.96	8.10- 9.73	15.35	25.65
25	Furniture and Fixtures	1.94	3.24	1.28	-				0.46	
26	Paper	5.09	7.52	2.81	0.02	11.39	9.09- 9.80	6.08- 7.24	10.16	
27	Printing and Publishing	7.61	10.55	6.43	0.01				0.40	
28	Chemical Products	3.02	5.54	9.30	5.41	0.07	0.14- 0.16	0.20- 0.25	Misc.	0.45
29	Petroleum and Coal Products	0.57	0.77	0.30	0.01	-	-	-	Misc.	-
30	Rubber and Plastic Products	2.46	3.63	5.71	0.09	0.09	0.12- 0.13	0.16- 0.19	0.15	
31	Leather	3.16	3.60	2.88	-	0.06	0.06- 0.09	0.10- 0.16	0.06	Misc.
32	Stone, Clay and Glass	2.46	3.58	4.10	0.01	-	-	-	Misc.	
33	Primary Metal Industries	1.75	2.22	4.19	2.39	-	-	-	Misc.	
34	Fabricated Metal Products	3.83	5.54	9.43	0.10	-	-	-	Misc.	
35	Machinery, except electric			6.32	5.37	-	-	-	Misc.	Misc.
36	Electric and Electronic Equipment	1.52	2.74	5.64	0.33	-	-	-	Misc.	
37	Transportation Equipment	1.74	2.19	4.61	0.92	-	-	-	Misc.	
38	Instruments	0.83	1.37	0.81	0.03	-	-	-	Misc.	
39	Miscellaneous	0.85	1.24	0.68	-	1.21	1.95- 2.13	2.51- 2.99	1.21	0.10
	Process Wastes	103.24	106.18	88.62	16.98	34.78	32.10-34.49	26.61-30.63	30.09	31.13
	Plant Trash	Incl.	Incl.	Incl.	Incl.	11.80	19.85	26.40	N.A.	11.75
	GRAND TOTAL INDUSTRIAL WASTES	103.24	106.18	88.62		46.58	51.95-54.34	53.01-57.03		42.85
242x	Sawmills	32.80	11.50						13.61	

a - demolition only
only

f - forecast

b - construction
only

minor waste streams from cotton ginning and stockyards were left to be discussed under agricultural waste, and a major waste stream from supermarkets was left out because it was part of the municipal waste stream.

Combustion Engineering estimated that 93.66 x 10^6 Mg (103.24 million tons) of industrial solid wastes were generated in 1965. More than half that total was generated in the demolition and wood products industries; saw mills are by far the largest contributor to industrial solid wastes. As mentioned earlier, new uses are turning this waste into useful products, and consequently the amount of saw mill waste is dropping. Saw mills are industrial operations, but their waste is more akin to agricultural wastes, and is often discussed under that heading (See Table A-10). Alich (Ref. A-34), for example, reported that there are 105 x 10^6 Mg (116 million dry tons per year) of forestry waste, but goes on to say that two-thirds of that are mill residues. "Of the 76 million dry tons of mill residues, 50 percent is sold for various purposes, 25 percent is used as a fuel without sale, and 25 percent is unused (waste)" (Ref. A-34). Informal discussion with wood industry officials indicate that in ten years there will be essentially no wastage, and that the percent sold will increase.

Niessen and Alsobrook (Ref. A-14) used an approach similar to Combustion Engineering's, but also attempted to gather data on liquid wastes and on sludges. The data they reported was in tons per employee per year (TEY). These have been applied by Parsons to employment statistics developed by the Bureau of Labor Statistics (Ref. A-35) for 1970 to determine waste quantities. The calculated waste totals are 80.40 x 10^6 Mg (88.62 million tons) of solid wastes and 15.40 x 10^6 Mg (16.98 million tons) of liquid wastes for 1970, but these do not include demolition wastes. Taking that into consideration, their estimate of industrial solid waste is very close to that developed by Combustion Engineering.

The Niessen and Alsobrook TEY factors come from the very narrow base of northern New Jersey and western New York State. Those authors caution that the figures may not be reasonably representative of other areas; evidence of this possibility can be seen in their relatively high figure for Code 20: Food Products and low figure for Code 24: Wood Products.

IR&T (Ref. A-3) took a narrower view of wastes, more useful for investigating energy recovery possibilities, by studying only dry, combustible solid waste. IR&T also took a different approach than the other two studies, using a combination of material flow and input-output analysis to determine the ultimate disposition of all combustible material, either into products or into wastes. The waste quantities were aggregated into industrial groups whose members produce similar waste. Fortunately, these groups tend to be combinations of SIC Code groups, so the IR&T data retain some comparability with the other studies.

The IR&T study reported 42.26 x 10^6 Mg (46.58 million tons) of industrial combustible solid waste in 1967, less than half that estimated by Combustion Engineering. In both estimates, wood product waste is the largest single contributor. Because it is combustible waste in both cases, the estimate should be similar; there is not sufficient information to account for the discrepancy shown. Similar disagreements exist in the food processing and textile categories, and as a result the close agreement in the paper, printing, and publishing category is surprising.

Two important re-analyses of the IR&T data have been made. Smith (Ref. A-36) divided the IR&T waste quantity aggregations to fit the SIC code more closely, and Huffman (Ref. A-37) updated the quantities to 1970. As a result of Smith's breakdown, the quantity for sawmill operations can be separated as 12.35 x 10^6 Mg (13.61 million tons) per year; this is still less than half of the 29.76 x 10^6 Mg (32.80 million tons) estimated for 1965 by Combustion Engineering, but may not be unreasonable if the resource recovery of sawdust proceeded more rapidly than Combustion Engineering estimated in giving the 1975 forecast at 10.43 x 10^6 Mg (11.50 million tons).

For liquid and sludge waste, Niessen and Alsobrook developed an estimate of 15.40 x 10^6 Mg (16.98 million tons) per year. The major contributing industries were the chemical products, machinery, and primary metals industries (Ref. A-14, Table 8). The only other source of data on liquid industrial wastes that was located was a report put out in 1968 by the U.S. Department of the Interior, based on 1963 information (Ref. A-38). This report gave a figure of 8.2 x 10^6 Mg (9 x 10^6 tons) of settleable and suspended solids in industrial waste waters in 1963, primarily from the food products, primary metals and paper industries.

Characteristics

Smith, in re-analyzing the IR&T waste quantities, also provided a more useful breakdown of the heat content of these wastes, shown in Table A-9.

Robert G. Schwieger (Ref. A-39) gave some examples of typical industrial wastes with significant heating value:

	Average Heating Value (As Fired)	
Waste	MJ/kg	Btu/lb
Gases:		
Coke-oven	45.82	19,700
Blast furnace	2.64	1,139
Carbon monoxide	1.34	575
Refinery	50.71	21,800
Liquids:		
Industrial sludge	8.61 - 9.77	3,700 - 4,200
Black liquor	10.23	4,400

Waste	Average Heating Value (As Fired) MJ/kg	Btu/lb
Sulfite liquor	9.77	4,200
Dirty solvents	23.26 - 37.22	10,000 - 16,000
Spent lubricants	23.26 - 32.56	10,000 - 14,000
Paints and resins	13.96 - 23.26	6,000 - 10,000
Oily waste and residue	41.87	18,000
Solids:		
Bagasse	8.37 - 15.12	3,600 - 6,500
Bark	10.47 - 12.09	4,500 - 5,200
General wood wastes	10.47 - 15.12	4,500 - 6,500
Sawdust and shavings	10.47 - 17.44	4,500 - 7,500
Coffee grounds	11.40 - 15.12	4,900 - 6,500
Nut hulls	17.91	7,700
Rice hulls	12.09 - 15.12	5,200 - 6,500
Corn cobs	18.61 - 19.31	8,000 - 8,300

Forecasts

The IR&T study included a forecast of combustible industrial solid waste categories for the years 1980 and 1990, using an input-output forecasting model developed by Clopper Almon at the University of Maryland. These forecasts are shown in Table A-8. There is insufficient comparative data available to permit any comment, other than it is interesting to note that by 1990 plant trash is projected to be almost half of the total.

AGRICULTURAL WASTES

Types

Agriculture includes both the production of crops and the raising of livestock; forestry is included, since trees are a form of plant crop. The principal constituents of agricultural wastes are field crop residues, livestock manure, and forest slash, with small quantities of animal carcasses and

TABLE A-9A. CHARACTERISTICS OF COMBUSTIBLE INDUSTRIAL SOLID WASTES (1967)

(SI Units)

SIC Code		Gg (dry)/y	TJ/y	MJ/kg
15, 16, 17	Construction	1 179	27 327	23.17
20	Food Products	648	12 556	19.38
22, 23	Textiles and Apparel	264	5 486	20.78
24	Wood	13 927	324 020	23.26
25	Furniture & Fixtures	413	9 601	23.26
26	Paper	9 213	161 008	17.47
27	Printing & Publishing	366	6 436	17.56
30	Rubber & Plastics	138	4 115	29.84
31	Leather	53	1 266	23.65
19, 21, 28, 29, 32-39	All other Mfg.	1 098	26 799	24.41
		27 713	578 617	20.88 (Average)

TABLE A-9B. CHARACTERISTICS OF COMBUSTIBLE INDUSTRIAL SOLID WASTES (1967)

(English Units)

SIC CODE		10^3 Tons (Dry)/year	10^{12} Btu/year	Btu/lb
15, 16, 17	Construction	1,300	25.9	9,962
20	Food Products	714	11.9	8,333
22, 23	Textiles and Apparel	291	5.2	8,935
24	Wood	15,352	307.1	10,002
25	Furniture & Fixtures	455	9.1	10,000
26	Paper	10,156	152.6	7,513
27	Printing & Publishing	404	6.1	7,550
30	Rubber & Plastics	152	3.9	12,829

TABLE A-9B. CHARACTERISTICS OF COMBUSTIBLE INDUSTRIAL SOLID WASTES (1967) (Cont)

(English Units)

SIC Code		10^3 Tons (Dry)/year	10^{12} Btu/year	Btu/lb
31	Leather	59	1.2	10,169
19, 21, 28, 29, 32-39	All other Mfg.	1,210	25.4	10,496
		30,548	548.4	8,976 (Average)

After Smith, Ref. A-36

agricultural chemical wastes. Forest slash includes those wastes left in the forest during logging operations; logging residues accumulated at saw mills may be included under agricultural or industrial wastes. Similarly, the slaughtering and meat packing industry accounts for most of the animal carcass wastes.

Agricultural wastes are almost entirely organic; exceptions are crop residues such as rice hulls which contain significant concentrations of silica. Not all agricultural wastes are directly combustible, however, with fresh animal manure and wood wastes having very high water content. Because of the variability of the moisture content of agricultural wastes, data on quantities and characteristics must be stated on a dry basis for comparability.

Quantities

Estimates of the quantities of agricultural waste are shown in Table A-10. Crop and animal wastes are generally calculated by applying waste generation factors to statistics of agricultural production compiled by the U.S. Department of Agriculture. For example, Taiganides and Hazen (Ref. A-40) have reported the following properties of farm animal excreta:

	Hens	Swine	Cattle
Animal weight	1.8 - 2.3 kg (4-5 lb)	45 kg (100 lb)	450 kg (1000 lb)
Wet manure, weight/day	0.11 kg (0.25 lb)	3.2 kg (7.0 lb)	29.0 kg (64.0 lb)
Total Solids, % wet basis	29.0	16.0	16.0
Volatile solids, % dry basis	76	85	80

TABLE A-10. SOLID WASTE GENERATION FROM AGRICULTURE AND LOGGING

	Eliassen (Ref. 1) 1966	IR&T (Ref. 3) 1966		R.M.P. Calcu. 1970	Grantham (Ref. 29) 1971	Anderson (Ref. 5) 1971	Anderson (Ref. 5) 1971	Poole (Ref. 41) 1973	Ellis (Ref. 42) 1973	Alich (Ref. 34, 43) 1973		Forest Service (Ref. 44) 1970 - 1973	
	Wet Total	Wet Total	Dry Avail.	Wet Total	Dry Total	Dry Total	Dry Avail.	Dry Total	Dry Total	Dry Total	Avail.	Dry Total	"Available"
						TERAGRAMS PER YEAR							
Crop Wastes	501	386	152.1	-	-	354	21	309	-	292	252		
Livestock Wastes	1418	1034	34.6	1257	-	181	24	41		33	24		
Logging Wastes	23	43	23.5	-	29.7	50	5	24	142	36	34	1046	41
Total	1942	1463	210.2			585	50	374		361	310		
Sawmill Waste	-	-	12.3	-	22.0	-		10.2	15	17	17		17
						MILLION OF TONS PER YEAR							
Crop Wastes	552	425	167.7	-	-	390	23	341		322	278		
Livestock Wastes	1563	1140	38.1	1386	-	200	26	45		36	26		
Logging Wastes	25	47	25.9	-	32.7	55	5	26	157	40	38	1153.62	45
Total	2140	1612	231.7			645	54	412		398	342		
Sawmill Waste	-	-	13.6	-	24.3	-		11.2	17	19	19		19

From this data the following can be calculated:

	Hens	Swine	Cattle
Wet manure, Mg/year/animal	0.0041	1.159	10.596
Volatile solids, Mg/year/animal	0.0009	0.158	1.356

The Statistical Abstract of the United States, (Ref. A-45) gives the following farm animal population figures for 1970:

Cattle	112 303 000
Swine	56 655 000
Poultry	431 000 000

The resulting total manure and dry organic solids from these animals would be:

	Wet Manure	Volatile Solids
Cattle	1190 x 10^6 Mg	152 x 10^6 Mg
Swine	65	9
Poultry	2	0.4
Total	1257 x 10^6 Mg	161.4 x 10^6 Mg (13%)

This calculation does not include sheep, horses, pets, and possibly some poultry, so that the total wastes are understated.

The resulting wet basis figure of 1257 x 10^6 Mg (1385.6 million tons) agrees reasonably well with the Eliassen (Ref. A-4) estimate of 1563 million tons and the IR&T (Ref. A-3) estimate of 1140 million tons. The range between the high and low estimates, 423 million tons per year, is about plus and minus 15% about the average of the three values. For gross calculations, the best permitted by the available data, this is very close agreement.

The quantities calculated above are wet manure weights for the entire animal population, not just confined animals. Less than one-fourth of the total manure generated occurs in sufficient concentrations to make collection and disposal necessary and economical (Ref. A-3). In addition, manures contain major amounts of moisture, on the order of 84% moisture for cattle, 75% for poultry, 90% for sheep and 95% moisture for hogs (Ref. 3). The weight of dry solids requiring disposal is therefore a small fraction of the total wet weight generated. This explains why the Alich, IR&T "available" and Poole estimates are so small. For energy calculation purposes this dry, available weight should be used, keeping in mind that the wet, available weight must be used for physical handling calculations.

Similar calculations can be made for agricultural crop wastes. Table A-11 gives residue factors for major crops. Crop residues are usually defined as the above-ground portions of the crop plant that are not harvested. There is reasonable agreement between most of them, with two notable exceptions. The maximum ratio of high to low values is 3.2 to 1, except for corn (11 to 1) and sugar cane (32 to 1). The variation found for corn is quite possibly due to an error by IR&T in the value assumed for harvest per acre. The IR&T data imply 0.043 kg/m^2 (0.191 tons/acre), while Poole's data imply a value of 0.57 kg/Mg/m^2 (2.55 tons/acre), and Knutson's a value of 0.66 kg/m^2 (2.96 tons/acre). The variation found per sugar cane is more likely due to a difference in the definition of residues. Poole's value specifically excludes bagasse, considering it a food processing residue. Eliassen's estimate can probably also be explained this way. Alich and Inman (Ref. A-46) show a range of aboveground, dry biomass yields of 2.80 to 5.82 kg/m^2 (12.5 to 26 tons per acre) for sugarcane, which indicates that IR&T's residue figure of 6.16 (wet) and 2.46 (dry) kg/m^2 (27.5 tons (wet), 11 tons (dry) per acre) includes bagasse. The NSF and ERDA sponsored work of Alich (Ref. A-34, A-43) is the most recent available, and its exacting methodology commends use of the crop residue data to all interested in this waste source.

The calculation of total residue quantities is made by applying the Table A-11 factors to statistics of weight or area harvested. Investigators who have developed these factors have established that three crops - corn, wheat, and soybeans, in that order - produce two-thirds to three-quarters of the agricultural crop waste total (Refs. A-4, A-3, A-34, A-41, A-43).

The quantity of forest waste varies according to the logging practices followed and the definitions used in enumerating residue. When wood prices are high, tighter control is kept on the generation of residues. The definition used also have an impact, because the conservative definitions followed by the U.S.D.A. Forest Survey Teams include only salable wood left in harvested areas. Wood under 10 cm (4 in.) in diameter and non-salable trees are not included, nor are residues outside of harvested areas. The estimates by Eliassen (Ref. A-4), IR&T (Ref. A-3), Poole (Ref. A-41), and Grantham and Ellis (Ref. A-29) were made on this basis. Ellis (Ref. A-42) included all residues in harvested areas, recognizing that new wood harvesting technology such as chipping and hogging, would permit much of this residue to be profitably used.

An estimate made by the U.S. Forest Service (Ref. A-44) went even further, estimating that non-commercial timber, forest harvest residues, other "removals" (land clearing and changes in operational land use), and unused primary manufacturing residues total as much as 1046 x 10^6 Mg (1153.62 million tons) (dry). Non-commercial timber is a one-time inventory, not an annually recurring quantity. Unused primary manufacturing residues and other removals due to changes in land use are outside the logging industry. When the definition of forest residues is made comparable to the definitions used in other estimates, the quantities are also comparable. Total forest harvest residues, including small branches, culls, and bark are estimated to be 113 x 10^6 Mg (130 million tons) (dry); residues on the more conservative growing stock basis are 41 x 10^6 Mg (45 million tons).

TABLE A-11. RESIDUE FACTORS FOR MAJOR CROPS

	Unit Weight of Dry Residue Per Unit Weight of Harvest					kg of Residue per m² of Harvest (Tons of Residue per Acre of Harvest)			
	Eliassen Ref A-4	IR&T Ref A-3	Poole Ref A-41	Knutson Ref A-47	Alich Ref A-34, 43	Eliassen Ref A-4 Wet	IR&T Ref A-3 Wet	Poole Ref A-41 Dry	Knutson Ref A-47 Air Dry
Corn	9.42	5.63[c]	0.85	1.35	1.10	1.0 (4.5)	0.60 (2.69)	0.49 (2.17)	0.90 - 1.0 (4.0 - 4.5)
Wheat	0.661	0.472	1.50	1.0		0.29 (1.3)	0.21 (0.93)	0.32 (1.43)	0.34 - 0.36 (1.5 - 1.6)
Oats	0.915	0.929[d]	1.50	1.0		0.40 (1.8)	0.41 (1.83)	0.25 (1.13)	0.22 - 0.34 (1.0 - 1.5)
Barley	0.733	0.820	1.25	1.0		0.40 (1.8)	0.45 (2.0)	0.27 (1.21)	0.31 - 0.34 (1.4 - 1.5)
Cotton	3.42	3.20	3.00	1.5	2.45	0.45 (2.0)	0.42 (1.88)	0.48 (2.12)	0.34 - 0.45 (1.5 - 2.0)
Soybeans	1.09	0.554	0.85	-		0.45 (2.0)	0.22 (1.0)	0.16 (0.71)	-
Rice	0.531	0.602[e]	0.85	1.35		0.67 (3.0)	0.76 (3.4)	-	0.67 - 0.83 (3.0 - 3.7)
Sugarcane	0.004	0.129	0.23	-		0.11 (0.5)	6.16 (27.5)	0.25[g] (1.10)	-
Vegetables	0.102	0.114	-	-		0.67 (3.0)	0.75 (3.33)		0.27 - 0.49 (1.2 - 2.2)

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a. Assuming 60% moisture in residue, except for vegetable residues which have 80%
b. Calculated by Parsons using Eliassen's waste rates and IR&T harvest rates
c. Recalculated by Parsons from IR&T data; original value was 0.554
d. Recalculated by Parsons from IR&T data; original value was 0.960
e. Recalculated by Parsons from IR&T data; original value was 0.378
f. Calculated by Parsons from IR&T data
g. Excluded bagasse

The annual quantities of logging wastes reported in Table A-10 are expected to decline. Twenty years ago, perhaps only 50% of the above-ground tree reached the consumer as a product; today, an estimated 20% is still wasted, but in ten years wastage is expected to be near zero.

In developing Table A-10, an attempt has been made to identify a number of knowledgeable sources rather than quote every possible reference. Given the varying definitions and bases for calculation, there is reasonable agreement. Once the difference between wet and dry bases is understood, it represents no problem, but the difference between "total" and "available" is not always clear. Anderson (Ref. A-5) assumes that only 8% of the total crop wastes would be available for conversion to energy, citing its wide dispersal. Alich (Ref. A-34, A-43) assumes that 86% of the total crop waste is available, but then reports livestock wastes from confined animals only in the total, and assumes that 76% of that is available. Many authorities reject offhand the use of agricultural residues as being "too diffuse" for consideration for conversion to energy, but the quantitative studies to establish the probable economics are still in progress (Ref. A-43). A simple comparison with urban waste loadings demonstrates that the situation is one requiring additional analysis. The highly urbanized County of Los Angeles now disposes of an average of 0.85 $kg/m^2/year$ (3.8 ton/acre/year) while a typical city within it such as Pasadena currently sends 1.52 $kg/m^2/year$ (6.8 ton/acre/year) to landfills. These values are "as generated" (water present) and include wastes from all sources, including demolition rubble. Farm areas generate on a dry basis (Ref. A-6) 1.01 $kg/m^2/year$ (4.5 ton/acre/year) for corn crop wastes, and 0.67 kg (3.0 tons) each for rice, sorghum, peanuts, potatoes, and sugar beets. The marginal costs for harvesting equipment to simultaneously cut (and bale or pelletize) stalks, leaves, and stubble should be low and clearly transportation costs to central processing plants should be as low as the comparable urban case.

While this demonstrates that potentially large quantities of agricultural wastes might be more readily available than previously considered, their actual usage for conversion to energy (either by combustion or chemical conversion to fuel) will be affected by factors other than average area density. Waste generation in farm areas is highly seasonal. Alich (Ref. A-34) says that 8.4% is generated in the first quarter of the year, 12.0% in the second quarter, 41.6% in the third, and 38.0% in the fourth. This variation can place severe constraints on processing plant utilization. The chief constraint, according to preliminary discussions of field waste conversion processes with agricultural authorities in Kansas and California, is probably requirements for the waste in high value applications on the farm itself. The discing under of crop wastes and manure for benefication of the soil structure is widely practiced, although no information has yet been found on minimum quantities truly needed for high crop yields. With increasing feed costs, farmers are able to sell or use their field wastes (e.g. wheat straw, corn stalks, and soybean waste) in prepared feeds that incorporate molasses and urea. Wheat straw is now selling in the $20-$21 per Mg ($22-$23 per ton) range. Alich (Ref. A-34) gives the following dispositions of crop residues.

Returned to soil	73.6%
Fed without sale	19.0
Sold	4.0
Fuel	2.8
Wasted	0.6
	100%

The quantities given in Table A-10, therefore, do not necessarily represent true wastes that currently have no economic value, but rather residuals from primary processes.

Characteristics

Schlesinger, Sanner and Wolfson (Ref. A-48) have calculated the heating values of the dry volatile solids found in agricultural wastes, and give the following figures:

Bovine waste: 16.54 MJ/kg (7,110 Btu/lb)

Rice Straw: 14.14 MJ/kg (6,080 Btu/lb)

Rice Hulls: 15.37 MJ/kg (6,610 Btu/lb)

Pine Bark: 19.42 MJ/kg (8,350 Btu/lb)

Corder (Ref. A-49) states that non-resinous woods and barks have higher heating value ranges of 18.61 - 19.77 and 17.21 - 22.79 MJ/dry kg (8,000 - 8,500 and 7,400 - 9,800 Btu/dry pound), respectively, while resinous woods and barks fall in the ranges of 20.00 - 22.56 and 20.47 - 25.12 MJ/dry kg (8,600 - 9,700 and 8,800 - 10,800 Btu/dry pound), respectively. Typical moisture contents for commercial hogged fuel are cited as 40-55%, while bulk density values fall in the range of 0.096 to 0.208 g/cm^3 (6 to 13 pounds per cubic foot). Pelletized fuels made from numerous agricultural wastes have been inspected at Parsons, all of which sank in water, implying that they have a density greater than $1g/cm^3$ ($62.4\ lb/ft^3$).

Distribution

It is of interest to note from the raw SRI (Ref. A-50) data that eight states contain 67% of the available forest residues, nine states 60% of the crop residues, and seven states 48% of the manure available. A computer program developed by SRI is now being applied to the data to ascertain potential processing sites and the affect of seasonality on such a plant (Ref. A-43).

Eliassen (Ref. A-4) reports that over 70% of the wastes generated are due to 3 of the 22 crops listed: corn, soybeans, and wheat. Field waste of corn grown for grain accounts for 46% of the total crop waste. He notes that agricultural experts have estimated "that of the weight of corn crops grown for canning, about 50% is field waste, about 30% is process waste and less than 20% is actual corn in the can."

The high degree of regionality associated with agricultural wastes does not mean that conversion processes cannot be applied to them, but only that specific analyses should be conducted to establish how best to utilize the energy inherent in these residues.

Forecasts

IR&T (Ref. A-3) gives a total (dry basis) estimate for 1967 of 210.2 x 10^6 Mg (231.7 million tons), projected to 309 to 323 x 10^6 Mg (341 to 356 million tons) in 1980 and 362 to 407 x 10^6 Mg (399 to 449 million tons) (dry basis) in 1980. Anderson's base is higher, but he uses less than half the growth rate used by IR&T.

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APPENDIX B

CATALOGUE OF WASTE-TO-ENERGY PROCESSES

INTRODUCTION TO WASTE TO ENERGY PROCESSES

As discussed in Appendix A, many wastes can be converted to energy. This can be either heat energy for immediate use, or energy for use later, in the form of fuel. The basic waste-to-energy conversion processes can be conveniently categorized into the areas of combustion, thermo-chemical, biological, and mechanical systems. While these categories are not mutually exclusive, they do tend to indicate the primary action taken on the raw waste and some secondary action may then follow.

Combustion produces heat energy for immediate use. Technically, it is the only process that releases energy, since all the other processes produce fuel that must be combusted later when the energy is wanted for use, whether in a furnace, a car engine, or a stove.

Thermo-chemical processes such as pyrolysis, hydrogasification, and hydrogenation use heat and/or chemicals to break down complex materials and produce new solid, liquid, or gaseous fuels.

Biological processes also break down complex materials and produce new solid, liquid, or gaseous fuels.

Mechanical processes include sorting, size reduction, and drying to separate the combustible portion of wastes from the remainder. Unlike the other processes, which make both chemical and physical changes in the wastes to produce energy or a fuel, mechanical processing makes only a physical change.

There are some ten to twenty or more variations of each of the four basic processes given above. None of them are technologically new, although in some instances their application to the disposal of wastes has only been recently made. The divisions between these processes are not necessarily clear cut. Thermo-chemical processes, for example, combust some waste to produce the heat they need, and mechanical processing is a necessary step in many variations of the other processes.

A number of reasons exist for the proliferation of waste-to-energy conversion processes. There are many waste types, many energy/fuel markets, and many of the processes are technically very promising but not fully developed. The choice of a process for a given application depends on technical and economic factors, not as they are today, but as they will be in the future when the facility is operating. For example, in the days before stringent air pollution control regulations and when energy costs were low, municipal incinerators were built for waste disposal without energy recovery. When air pollution control legislation became effective, the design of incinerators included steam generators. These systems lowered the exhaust gas temperature enough to permit electrostatic precipitators to remove the particulate pollutants. These incinerators were still built essentially for waste disposal, however, and no special effort was made to insure that the quantity, quality, and location of the steam they produced was suitable for use. Today, as waste disposal and energy sources both become more expensive, waste disposal costs can be off-set by the revenue from energy sales. New incinerators are now being built predominantly with this in mind. In fact, incinerator is now a misnomer; these new facilities are more correctly called "waste-fired steam generators."

The costs of waste-to-energy processes vary over a broad range due to process differences, and because some produce energy while others produce a fuel. As mentioned at the beginning of this section, combustion is technically the only process that releases energy, with all the other processes stopping at producing a fuel. The cost of a combustion facility also typically includes the energy recovery system, usually a boiler, and may also include an energy use system, such as electric generators. It is, therefore, generally the most expensive per ton of waste disposal. However, because a modern combustion system converts waste to a final energy form in one facility, it may be the most efficient in terms of energy conversion. In terms of capital costs, the thermo-chemical processes tend to be the next most expensive, biological processes next, and mechanical processes least. It is extremely important to note that these are general tendencies, and that process costs are very sensitive to the specific situation.

In comparing similar processes, a useful concept is net energy output efficiency. Basically, efficiency is output divided by input, and expressed as a percentage. If waste with an energy content of 1000 MJ is put into a process and 500 MJ comes out, the process is 500/1000 = 50% efficient. Waste is not the only input to a waste-to-energy process, however; there is also electrical or mechanical energy and often auxiliary fuel. Simply adding these energies to the waste input is inaccurate, because, in a closed system, a portion of the output energy must be diverted to make these inputs. Therefore these inputs are debits against the gross energy output and the result is net energy output. Net energy output efficiency is then net energy output divided by waste energy input, expressed as a percent. This means that efficiency figures will be lower than most developers would like to see, and that systems that consume more energy than they produce will show negative efficiencies.

MECHANICAL PROCESSES

The initial steps in waste-to-energy systems are a series of mechanical processes for controlling and preparing the waste. These processes can constitute an entire system producing a fuel, or can be the first of several stages that produce a fuel or energy. Mechanical processes can be grouped under four headings: materials handling, shredding and other size reduction, sorting and classifying, and drying.

Treatment of waste makes subsequent steps more efficient and improves the potential for energy and material recovery. Many wastes are highly heterogeneous mixtures of materials. The product becomes much more homogeneous by shredding the waste to achieve a relatively uniform, small particle size; by sorting and classifying the waste to concentrate the energy fraction; and by drying the waste to remove water. This improves the ease and efficiency of energy conversion and increases the quantity of energy that can be recovered from a given amount of raw waste. In some instances the improvement in energy recovery is sufficient to justify the extra expense of mechanical processing. In other cases, processing is justified because it makes a salable fuel or permits the use of existing boilers and other equipment.

Materials Handling

Materials handling processes include receiving, weighing, moving, and storing of raw materials, materials in process, process residues, and products of processing.

Many waste gases contain a significant amount of sensible heat that can be recovered in a heat exchanger for use. Some waste gases, such as coke oven gas, can be used as low grade fuels in other processes, while others have value for the chemical raw materials they contain. In any case, the gas usually requires removal of contaminants before it can be transported by pipeline, stored, and eventually used. The cleaning and removal of contaminants to make waste gas suitable as fuel, as a chemical raw material, or to permit disposal to the atmosphere, is very often the most complex and expensive part of the entire gas handling problem and may govern the ultimate use or disposal of it.

Liquids can be received at a disposal facility by tank truck or pipeline and weighed in the truck or measured by a pipeline flow meter. Many waste liquids are highly corrosive or toxic, requiring care and special materials and equipment to handle them successfully. Others are very viscous and will not pour without some application of heat, while still others contain a heavy load of solids that tend to settle out and plug handling equipment. There is no single method of handling and disposal of waste liquids that will satisfy all requirements; the specific waste liquid or class of waste liquids must be considered on an individual basis.

Solid wastes nearly always arrive at the disposal facility by truck, which is weighed before and after dumping the waste in order to record quantities for billing and plant operational records. There are presently two basic arrangements for receiving the waste. One utilizes a deep concrete pit into which the waste is dumped from the truck and subsequently handled and moved into further processing equipment by an overhead travelling crane equipped with a clamshell or grapple type bucket. The second uses a level concrete floor upon which the waste is dumped from the trucks and subsequently piled and moved into further processing by a large rubber-tired front-end loader. Both arrangements have been used successfully. It is claimed that the level floor (tipping floor) is more efficient at rates below 36 Mg (40 tons) per hour, while the pit type operations is more efficient at rates greater than this (Refs. B-1, B-2, B-3). There is considerable doubt on this matter and the designer should carefully consider all economic, operational, and safety factors before proceeding.

Recovered metals, glass, and residue prior to truck or rail shipment may be stored temporarily in a metal bin. The real storage problem may be found with the light fraction of shredded waste. The bulk density is low, approximately that of the original mixed waste, and hence the required storage volume is very large. The material has been found to compress in storage and be very difficult to remove. In straight sided storage structures or silos it has a strong tendency to bridge, making removal from the bottom difficult and hazardous. There are several proprietary storage and retrieval systems that have been or could be used for shredded waste. To date, those that have been tried have not shown outstanding success or dependability.

The transport methods for solid waste vary considerably, depending on the method of energy and/or material recovery. The various processing methods involve one or more types of material handling equipment such as slat or pan conveyors, belt conveyors, screw conveyors, vibrating feeders, pneumatic conveyance pipelines, and water slurry pipelines.

Some special handling characteristics of solid waste are:

- High dirt, metal, and glass content causes processed waste to be abrasive and especially hard on pneumatic conveying equipment. As processing progresses and more dirt, metal, and glass is removed, this abrasive characteristic diminishes, but never disappears.
- The tendency to bridge in storage has been discussed above. In addition, the material tends to migrate into conveyor drive machinery and clog it unless it is well protected.
- The handling and processing of waste creates dust, which should be contained and/or removed for health reasons. Dust control equipment may be a large part of the investment in a processing facility.
- The high moisture content contributes to corrosion of storage and processing equipment.
- Hazardous chemicals, pressurized containers, and explosives may be present.

Shredding and Other Size Reduction

Solid wastes have a wide range of particle sizes, making handling and processing difficult. Primary and secondary size reductions are relatively expensive, but often necessary. There are eleven basic types of size reduction equipment commercially available - crushers, cage disintegrators, shears, shredders, grinders, cutters and chippers, rasp mills, drum pulverizers, disc mills, wet pulpers, and hammermills (Ref. B-4, B-5, B-6). The general term "shredder" covers all of these types except for the wet pulpers.

The most popular type of shredder is the hammermill, which has a series of hammers, either rigid or swinging, attached to a horizontal or vertical rotating shaft. The hammers range in weight from 6.8 to 225 kg (15 to 500 lb) each and the forces they generate in the hammermill are sufficient to break almost any waste. The major problem materials are cable, which tends to become entangled in the hammers; rugs, which absorb the hammer impacts; and hard steel objects such as automobile crankshafts, which dull the hammers.

Hammermills are used to shred both MSW and forest waste. In the forest products industry, shredders are called hogs; a hammermill is a no-knife hog. A knife-type hog, or chipper, is a large, heavy drum with hardened steel inserts; wood fed into the spinning drum is rapidly chipped. Both the no-knife and knife-type hogs are used to produce chipped, or hogged, fuel. The knife-type, being more sensitive to tramp iron and rocks, is usually used on debarked logs or off-spec lumber, while the no-knife type can handle bark and logs (Ref. B-7).

MSW can also be shredded by grinders. These are usually vertical shaft machines with gear-like wheels that grind the refuse against the housing side walls. The waste flows through the machine assisted by gravity. Vertical machines, whether grinders or hammermills, generally do not reject hard-to-shred items, but reduce all objects to a relatively uniform size.

Power requirements for shredding municipal solid waste range from 6.5 to 35 horsepower per ton-hour, with the power requirement increasing as the output particle size becomes smaller (Ref. B-6). Medium duty mills used for shredding MSW typically require 20 kW/Mg-h (25 horsepower per ton-hour) of throughput (Ref. B-6, B-8). A waste shredding facility processing 907 Mg (1000 tons) per day in one 8-hour shift would require shredders totalling 2.3 MW (3,125 horsepower).

Capital, maintenance, and operating costs for shredders have been investigated by the Midwest Research Institute for the U.S. EPA (Ref. B-6). Conclusions are based on very limited data and should not be used for any detailed design or study projects. As shown in Table B-1, MRI estimated that the total cost of shredding MSW would vary from $2.28/Mg ($2.07 per ton) at a capacity of 9 Mg/h (10 tons per hour) to $1.44/Mg ($1.31 per ton) at 45 Mg/h (50 tons per hour), and rising again to $1.53/Mg ($1.39 per ton) at 91 Mg/h (100 TPH). These costs are much lower than the costs reported in the EPA publication "Decision-Makers Guide in Solid Waste Management," which says that "for projects in which EPA has been involved, costs per ton range from $8.60 up to $10.60 ($9.48 to $11.68 per Mg)" (Ref. B-9). These costs, however, are total project costs that include hauling and land-filling costs for the shredded refuse. Other cities have reported lower costs, between $4.52 and $5.29 per Mg ($4.10 and $4.80 per ton), for similar projects (Ref. B-9).

A number of technical papers have been written on municipal solid waste shredding (Refs. B-11, B-12, B-13). "Solid Waste Shredding and Shredder Selection" (Ref. B-5) has a list of shredder installations as of mid-1974 and examples of shredder specifications; MRI's "Fine Shredding Study" (Ref. B-10) has a 1975 survey of shredders used or to be used for size reduction of MSW in the United States.

TABLE B-1. ESTIMATED COSTS OF SHREDDING MUNICIPAL SOLID WASTE, NOVEMBER 1975

(SI Units)

Capacity Mg/h	Capital cost[a] $/Mg	Maintenance cost[b] $/Mg	Operating cost[c] $/Mg	Total cost $/Mg
9.07	0.21	0.33	1.74	2.28
45.4	0.21	0.55	0.60	1.44
90.7	0.21	0.77	0.55	1.53

a/ Assuming $4409 per Mg-h, zero salvage value, lifetime of 20 years, 6% interest rate, and 7 hours of running per day;

b/ MRI estimate;

c/ Assuming 21 kWh/Mg, $0.02/KWh, and 1 1/2 men for 8 hours per day at $7 per hour.

(English Units)

Capacity tons per hour	Capital cost[a] $ per ton	Maintenance cost[b] $ per ton	Operating cost[c] $ per ton	Total cost $ per ton
10	0.19	0.30	1.58	2.07
50	0.19	0.50	0.62	1.31
100	0.19	0.70	0.50	1.39

a/ Assuming $4,000 per ton hour, zero salvage value, lifetime of 20 years, 6% interest rate, and 7 hours running per day;

b/ MRI estimate;

c/ Assuming 25 horsepower per ton/hr, $0.02/kWh, and 1 1/2 men for 8 hours per day at $7 per hour.

Source: Ref. B-10

The major advantage of dry shredding is the ability of the larger equipment to handle a wide range of mixed raw waste directly. High operating and maintenance costs could be considered the penalty for this versatility.

All of the equipment discussed above is for shredding relatively dry waste. It is also possible to shred waste wet in a machine called a hydrapulper, which is essentially an oversize blender. A complete waste disposal and resource recovery system using a Hydrapulper and processing wastes in a slurry has been demonstrated at Franklin, Ohio (Ref. B-14) and is planned for Hempstead, New York (Ref. B-15).

In operation, MSW is fed into the Hydrapulper, where a high speed rotating cutter chops the pulpable materials into a 3 to 4% solids-in-water slurry. This slurry, containing paper, food waste, plastics and most of the other organics, as well as glass and small pieces of metal, is withdrawn continuously from the bottom of the pulper. Larger, heavier objects--cans, stones and large pieces of metal--are ejected through a chute and removed. Recycled water is introduced into the system through the same chute, so that the heavy materials must drop down the chute against a counter-current flow of water, which very effectively carries the lighter materials back into the Hydrapulper.

A major advantage of the Hydrapulper is that it permits a very high fraction of the organic, combustible material to be recovered in a homogeneous form. A major disadvantage is the high volume of water required and the need for removal of the water before many energy recovery processes could be efficiently employed.

A semi-wet refuse pulverizing system under development in Japan performs the classifying function at the same time (Ref. B-16). The system separates components by utilizing the differences in resistance to destruction. It consists of a horizontal rotating drum with screens having two kinds of scrapers rotating at different speeds in both screens. Refuse moving through the drum is classified by the screens according to the pulverizing time and screen size, which in turn depend on the material. A limited amount of water is used to reduce the strength of papers, permitting their extraction at lower power consumption.

Sorting and Classifying

Sorting and classifying processes include manual sorting, screening, magnetic metals separation, magnetic eddy current separators (aluminum magnet), wet and dry density separators, optical sorters, and electrostatic separators. Many of these systems were originally developed in the mineral, agricultural, or manufacturing industries. All of them, however, have been especially adapted for handling wastes.

Manual Sorting--

Hand picking and sorting refuse from conveyors is the traditional means of separating solid waste. As late as 1968 it was reported to be the most widely employed separating technique (Ref. B-17). Two prominent manual sorting facilities were the Lone Star Organics plant of Metropolitan Waste-Conversion Corporation in Houston, Texas, and Sanitary Refuse Collectors in Montreal, Quebec (Ref. B-18). Both used human operators to recover salvageable materials and bulky wastes; ferrous metals were removed by magnets. Both plants closed in the early 1970's for economic reasons.

At the Lone Star plant, it has been reported that approximately 551 to 827 kg (1/2 to 3/4 ton) of newsprint and cardboard could be handpicked from mixed refuse by one man in an hour, corresponding to 1.4 to 2.2 man-hours per Mg (1.3 to 2 man-hours per ton) of raw refuse (Ref. B-17).

Clean Steel Company of Carson, California is currently using manual sorting as part of a car-breaking operation. Stripped, crushed automobiles were shredded and then passed through a series of screens and other mechanical separators. Human operators hand picked the product conveyors coming from each mechanical separator to remove either impurities or the desired salvage material.

In sorting municipal solid waste there will be few times when manual sorting can be economically justified.

Screens--

If the materials have definable size differences, a screen may be used to separate them. The most common form of classifying screen is the trommel, an inclined, rotating drum with sized holes. It is commonly used to remove dirt from fuel bark before it is hogged or to sort wood chips (Refs. B-7, B-19). Similar devices have been proposed for classifying municipal solid waste into a fraction to be reground and a fraction for further separation processing (Refs. B-17, B-20). Other dry screen designs include vibrating tables, rotating discs, and air blown tables (Ref. B-7). Most of these have been developed in the mineral extraction industries, and design for screening municipal solid waste is still relatively new and requires experimental verification (Ref. B-17).

A trommel has a natural drying effect that can be enhanced by adding a hot air blower, which may be of benefit in reducing clogging of moist waste (Ref. B-21).

Screens are also used in wet classification processes. The Black Clawson Company's process being demonstrated at Franklin, Ohio uses a number of cylindrical screens kept clean by the pulsating action of a rotor turning inside the screen (Ref. B-14).

Magnetic Metals Separation--

The separation of ferrous (iron) metals from municipal solid waste is done magnetically. A simple permanent magnet may be sufficient for removing an occasional nail or other piece of tramp iron from bark or sawdust fuel passing on a conveyor belt. For removing magnetic metals from municipal solid waste, however, either a drum type or a belt type system with electromagnets is preferred. They are similar in principle with a magnet being placed inside the drum or behind the belt to hold the ferrous metals while the remainder of the refuse falls away. Then, as the drum rotates or the belt moves, the ferrous metals are carried beyond the influence of the magnets and also fall away. For thorough separation it may be desirable to have a multistage system, because iron and steel tend to carry along pieces of paper, cardboard and plastic from the refuse (Ref. B-18).

Eddy Current Separators--

The separation of non-ferrous metals, such as aluminum, copper, and zinc from municipal solid waste using eddy current effect has been demonstrated by Occidental Research Corporation (Ref. B-22), Combustion Power Company (Refs. B-4, B-23), Eriez Manufacturing Company (Ref. B-17), and others. Most non-ferrous metals and alloys are non-magnetic, so the steady magnetic field of an ordinary magnet has no effect on them. However, in a moving magnetic field these metals develop an opposing eddy current field and are repelled. A linear induction motor placed underneath a conveyor belt carrying the refuse can provide the necessary field to deflect non-ferrous metals into a collection bin. In practice, a significant percentage of other materials is also deflected. Certain metals, notably stainless steel, are not affected. The repulsive force depends greatly on the size and shape of the metal piece to be deflected. These factors limit the present usefulness of eddy current separators.

Density Separators: Dry and Wet--

Density, or gravity, separators include air classifiers, vibrating tables, dry fluidized beds, light and heavy media flotation, and rising current separators. They all work by creating a condition in which the relatively low density materials are carried up by air or a liquid, while the higher density materials drop out. Because the low density materials tend to be combustibles and the high density materials tend to be non-combustibles, density classifiers are a relatively efficient means of separating them.

In an air classifier, refuse is allowed to drop off the end of a conveyor. As it falls, it is subjected to a flow of air either vertically upward or horizontally, which blows the lighter materials into a collector while the heavier materials fall into another collector. Internal arrangements of baffles, air blowers, collectors, and other equipment can be varied to suit the job (Refs. B-4, B-18).

Three different refuse-to-energy systems, supported in part by U.S. EPA grants, that use vertical air classifiers are being developed in St. Louis, San Diego, and Menlo Park (CA). The results they have achieved using air classifiers are similar: the light fraction represents 75% to 80% of the input and is about 90% combustible, with the remaining being light foil and some fine glass and dirt (Refs. B-22, B-24). The chief drawback of air classifiers is that they classify materials not only by density but also by form. A piece of aluminum foil, for example, may rise if it is a sheet but fall if it is balled up. For best results the input to an air classifier should be shredded, dried, and screened to a uniform size.

The U.S. Bureau of Mines has done extensive studies with wet and dry density classifiers, and has developed a prototype materials separation system (Refs. B-20, B-25, B-26). Stanford Research Institute has developed a zig-zag air classifier, originally for sorting edible beans, that also shows promise in classifying municipal refuse. Its chief advantage is that the refuse is bounced and tumbled at each turn of the separation column, giving better classification of the lights and heavies (Ref. B-18).

Rising current separators are very similar in design to air classifiers, except that water, rather than air, is the separating medium (Refs. B-14, B-23).

Slightly different techniques are used in froth flotation, heavy media, and fluidized bed separators, all of which use the buoyancy characteristics of the materials to be separated. Froth flotation can be used to recover finely ground glass from a mix of glass chips, rocks, brick, bones, and heavy plastic. The mix is slurried with appropriate reagents that are selective for glass; a froth is created, and the glass is floated out of the mix and washed (Ref. B-22). Heavy media flotation takes advantage of the fact that heavy solids, such as ferrosilicon, magnetite, or galena, when finely ground and mixed with water, provide a suspension that closely duplicates the properties of a true heavy liquid. Specific gravities ranging from 1.24 to 3.4 can be made. Pure aluminum, with a specific gravity of 2.70, can be made to float or sink, as required. As with many solid waste separation techniques, practical and economical equipment requires considerable testing and modification to be truly effective and R&D is continuing (Refs. B-17, B-23).

Fluidized-bed separators have a bed of fine material, such as sand, through which air is blown; the bed then behaves very much like a true liquid (Ref. B-18). Warren Spring Laboratory of the British Ministry of Technology demonstrated a fluidized-bed separator in 1967, and others have tried the technique (Ref. B-27).

Density separators used in the agriculture and mineral industries, such as stoners, Osborne tables, jigs, and Wilfley tables have been tried with municipal refuse. The usual experience is that municipal refuse is so heterogeneous that extensive modification to the equipment is necessary for it to work (Refs. B-4, B-17, B-18).

Other Separation Methods--

The previously mentioned techniques are the principal ones being used or developed for classifying municipal solid waste. Any physical, chemical or electrical property that can be measured offers the possibility of development of a new sorting system. Two of the more important are optical sorting and electrostatic separation.

Optical sorting has been developed to separate the three predominant glass colors: clear (flint), green, and amber. The machine, manufactured by the Sortex Company of North America, is able to sense and reject material having light transmission qualities different from a standard glass. Only one color can be sorted at a time, and the glass must be graded by particle size. Individual particles drop through a light beam in an optical selection box, where their color is compared to a filter. When an off-color piece crosses the beam, electronic circuits cause a pneumatic valve to open and an air jet blows the piece to one side after it falls clear of the optical selection box. The classified glass still has a small percentage of particles that should have been rejected, varying with the mix in the input glass and the processing rate (Refs. B-4, B-23, B-25).

Electrostatic separation of conductors and non-conductors has been demonstrated. Dry waste to be separated is exposed to a high intensity electrostatic charge and falls on a rotating drum having the opposite charge. Materials that conduct electricity, such as metals, lose their charge rapidly, but non-conductors, such as glass and plastics, retain their charge and are attracted to the drum. As the drum rotates, the conductors fall off into a bin, but the non-conductors cling to the drum until wiped off into a second bin (Refs. B-4, B-23, B-28, B-29). Electrostatic separation is size-sensitive, and would have to be repeated to separate wastes having a range of particle sizes. Equipment made by at least two manufacturers have been used in industry successfully.

Drying

Drying systems can be classified by the manner in which the material is heated and moved through the dryer. There are four types of heating systems: convective, such as a hair dryer; conductive, such as a clothes iron; radiative, such as an infra-red lamp; and dielectric, such as a microwave oven. At the present state of the art, only convective systems are of sufficiently low cost to be considered for drying waste.

Among convective dryers, the eight systems for moving the material through the dryer are individual trays, band or belt conveyors, wiped trays, vibrating conveyors, rotary drums, fluid beds, airlifts, and sprays. Except for the first two, all are used for drying waste materials.

Multiple hearth dryers are a stack of wiped trays, each of which has one or more radial openings. Either the tray or the wiping arm can rotate; material falling on one tray is pushed around to the next opening where it falls to the shelf below and is leveled by a raking arm. Hot air is circulated through the enclosed stack of trays to carry off moisture. This type of dryer is often used with sewage sludges, which have a high water content; in some designs the sludge is burned on the lower trays to provide the heat for drying.

Vibrating conveyors, rotary drums, and airlifts are also used for sorting and can often have a dual function.

Air is used in vibrating conveyors to partially fluidize the waste for better particle separation. The natural drying effect that this provides can be further enhanced by using hot, dry air.

A rotary drum trommel screen has a natural drying effect that can be enhanced by adding a hot air blower (Ref. B-21). Rotary drum driers used to dry agricultural products and hogged wood fuel are made by a number of companies. Several of these are proposing systems for preparing dry fuel from municipal solid waste (Ref. B-30). Rotary drum dryers usually have vanes or "flights" on the outer shell and down the center of the drum to lift the wet material and control its fall through the hot gas stream. By controlling the amount of oxygen present, very high temperatures can be used without combustion or explosion.

An airlift is essentially the same as an air classifier, and if drying requirements are relatively low, one piece of equipment could perform both functions. For more drying effect, a recirculating system might be required, so that only the driest pieces are light enough to be carried out of the airlift. If this is done, close control on input particle size is necessary. One company makes a "Hot Hog" that is a hammermill, air classifier and dryer all in one. Bark or wood is dropped down a stack against a flow of hot air. At the bottom of the stack is a shredder that chops the feed until the pieces are sufficiently small and dry to be lifted back up the stack by the hot gases and out to a separator (Ref. B-7).

A rotary dryer is capable of handling a large throughput of material, but the evaporative capacity is relatively low. The airlift dryer has a much higher evaporative capacity, but a small throughput of material. The fluid-bed dryer has both a high throughput and a high evaporative capacity. Wet wastes are continuously introduced to the drying chamber and discharged as a dry product. Hot gas is blown through a distributor plate to partially or wholly suspend the particles in the hot gas stream. Any particles carried out by the exhaust gases are caught in a dust collector.

Spray dryers are very much like airlift dryers, and can handle high volumes of liquids or sludges. The waste liquid is allowed to flow out over a spinning disc, which flings it off in an umbrella-shaped cloud of droplets. The hot gas stream is usually introduced in parallel with the droplet cloud, and drying is accomplished in a fraction of a second. Spray driers work best when handling large volumes of solutions; for feed rates below 500 kg/h (1100 lb/hr), drum dryers become cheaper.

Waste Derived Fuels

Refuse can be burned without auxiliary fuel in its raw, as-received state, over a rather wide range of compositions. Von Roll of Zurich, Switzerland, has studied (Ref. B-4) mixtures of MSW, water, and inerts and established "self burning limits." Selected values from their work, at the limits of combustion, are as follows:

Water, wt-%	Non-combustibles, wt-%	Combustibles, wt-%
50	25	25
40	35	25
20	55	25
0	55	45

This information was developed with municipal solid waste in mind, but is generally applicable to other similar waste derived fuels. Water and non-combustible materials do not contribute to the heating value of the waste, so the greater the percentage of combustibles the more efficient the system will be.

A number of systems have been developed for processing waste so that it can be more conveniently handled, stored, and burned. Although the processes developed by various companies have some proprietary features, they all include initial shredding, magnetic removal of ferrous metals, and some sort of classifying system.

One of the simplest fuel-from-waste preparation processes takes bark from a tree de-barker, passes it over screens to separate the dirt, and then through a shredder. In order to remove more of the dirt and gravel while retaining a maximum of the combustible bark, more sophisticated screening and classifying devices have been developed, including rotary screens and fluid bed separators (Ref. B-7). At one time, large chunks of bark were hogged down to 5.0 to 7.5 cm (2 to 3 inch) nominal size for burning on grates, but today it is becoming more common to hog the bark or wood down to less than 0.5 cm (1/4 inch) nominal size for suspension firing in modern design furnaces.

The heating value of dry, resin-free wood is about 19.31 MJ/kg (8,300 Btu/lb), with little variation. Resin has a heating value of about 39.32 MJ/kg (16,900 Btu/lb) so resinous woods and bark have higher heating value than resin-free wood, going as high as 25.03 MJ/kg (10,860 Btu/lb) (Ref. B-31).

Finely hogged wood has served well as a waste fuel, but it also has close to 50% moisture, low bulk density, and non-uniform burning characteristics. In order to remedy these problems, various drying and pelletizing processes have been developed. One of these utilizes wet grinding to achieve a particle size of 3 mm (1/8 inch) in diameter and 12 to 18 mm (1/2 to 3/4 inch) long, and have a heating value of 20.93 MJ/kg (9,000 Btu/lb). In pellet form, the wastes are hydroscopically stable, ignite at 282°C (540°F), and burn at 2760°C (5000°F) (Ref. B-32).

Municipal solid waste can be similarly processed to produce a fuel, but additional steps are necessary to remove the ferrous metals and glass. In the hogged fuel processing, it is usually sufficient to place a permanent magnet above the flow at a convenient point to catch the occasional piece of tramp iron, but in a municipal RDF facility a more sophisticated system is required to capture all the food cans. A classifier and two stages of shredding are also often necessary. The new RDF facility being built for the City of Chicago is a good example of this type of system. Details are presented in Section 5.

Combustion Equipment Associates, Inc. (CEA) has taken this type of processing one step farther. The first version of their Eco-Fuel was a confetti-like fluff. To obtain the best suspension burning characteristics, however, a finer, more uniform product was necessary. This usually means a very high power requirement for grinding, but by adding a small amount of an inorganic chemical to what is essentially Eco-Fuel, it can then be ground in a hot ball mill with a relatively low power requirement. As a result, it is claimed that Eco-Fuel II can be ground to a size of 0.15 mm (0.006 in.) economically (Ref. B-33). The combination of chemical agent and hot ball mill, it is reported, reduces shredding and air classification requirements, uses less power, promotes recovery of ferrous and non-ferrous metals, and is environmentally attractive (Ref. B-34). Eco-Fuel II is a fine, dry, free-flowing powder with a high bulk density and an improved heating value. The fineness of grind and the uniformly high heat content facilitate combustion control and result in a complete burning of the organics. The fuel is flexible; it can be briquetted or slurried in oil (Ref. B-33).

In selecting a form for briquetting Eco-Fuel II, it was found that the shape of the common home barbecue briquette answered the problems inherent to coal conveying equipment (Ref. B-35). In creating this briquette, various binders may be used. Hydraulic pressure is then applied to produce the final product. The briquettes produced have sufficient anti-roll quality and weight to hold position on outdoor, utility-type conveyors. This product shape and stability has been successfully tested for its transport quality in existing coal conveying systems. In a typical analysis with an initial binding composition of 10% water, the bulk density was approximately 0.72 g/cm^3 (45 lb/ft^3), volatile matter around 65%, and total moisture remaining 4%.

CEA is developing a process for incorporating Eco-Fuel II in heavy oil (Ref. B-33). In Eco-Fuel II and oil mixtures containing up to 40% Eco-Fuel II, the final fuel product will retain 90% of the original heating value of the oil in a given volume. For example, No. 6 oil has a density of 0.92 g/cm^3 (7.7 lb/gal) and has an HHV of 39.71 MJ/dm^3 (142,450 Btu/gal). 40% Eco-Fuel II/60% oil mixture has a density of 1.07 g/cm^3 (8.9 lb/gal) and an HHV of 35.74 MJ/dm^3 (128,205 Btu/gal). CEA is developing oil burning equipment with the capability of combusting the combined fuel product.

Descriptions of Key Projects

On the following 4 pages are presented brief descriptions of typical projects producing waste-derived fuels.

NAME - City of Chicago Supplementary Fuel Processing Plant

TYPE - Mechanical MSW processing facility for producing refuse-derived fuel (RDF), which can be co-fired with coal in utility steam generators.

DEVELOPER - City of Chicago and Commonwealth Edison Company

HISTORY - Lacking suitable landfill sites, the City of Chicago has relied on incinerators for refuse disposal. Escalating incinerator construction and operating costs indicated the need for a new solution, and a study undertaken by the City in 1972 found that the St. Louis/Union Electric RDF system would best meet their needs. Design of the facility started in late 1973; construction began in 1974 and testing operations were initiated at the end of 1976.

PROCESS - The process is designed to produce RDF having a maximum 3.8 cm (1-1/2 in.) particle size. The MSW input rate is 72 Mg/h (80 TPH) on each of two processing lines. Refuse processing capacity is 1152 Mg/d (1280 TPD) in one 8 hour shift or 2304 Mg/d (2560 TPD) in two 8 hour shifts. From each 907 Mg (1000 tons) of raw refuse processed, 631 Mg (696 tons) of RDF with a 30% moisture content can be delivered, and 78 Mg (86 tons) of ferrous metals recovered. The higher heating value of the RDF is expected to be 13.20 MJ/kg (5674 Btu/1b).

MSW is weighed and dumped onto a tipping floor and then conveyed to a coarse shredder. The shredded refuse is divided by an air classifier into a light, largely combustible, fraction and a heavy fraction containing non-combustibles and overweight combustibles. The heavy fraction is magnetically separated to recover ferrous metals and the remainder is landfilled. The light fraction, containing approximately 85% of the organics in the raw refuse, plus some inorganic fines, is conveyed to a fine shredder whose output has a maximum size of 3.8 cm (1-1/2 in.). The processed RDF is carried by a pneumatic transfer system to storage bins adjacent to the power plant boilers. For burning, the RDF is removed from the storage bins by a mechanical system and blown into two boilers at Commonwealth Edison's Crawford Station, supplying approximately 7.5% of the main furnaces' heat requirements. The total RDF consumption of both units running at nameplate rating would be 978 Mg/d (1078 TPD), requiring 1406 Mg (1550 tons) of raw refuse to be processed. Only minor modifications to the boilers were required, involving penetration of the windbox and furnace wall by the pneumatic RDF transfer lines and changes to the boiler control systems. No changes were required in the ash handling or electrostatic precipitator systems.

ECONOMICS - Design and construction costs, which do not include any amount for land, construction management, working capital or startup, are estimated to total $18.8 million. At a production rate of 907 Mg/d (1000 TPD) the annual costs are expected to be $6.38/Mg ($5.79/ton) for amortization plus $6.94/Mg ($6.30/ton) for operations. These expenses will be offset by revenues from the sale of RDF and ferrous metals estimated to be $5.37/Mg ($4.96/ton) of refuse processed, resulting in a net annual cost of $7.85/Mg ($7.13/ton) of refuse disposed.

NAME - Solid Waste Recovery System, Ames, Iowa

TYPE - Refuse-derived fuel (RDF) and materials recovery plant

DEVELOPER - City of Ames, Iowa

HISTORY - As an alternative to continued landfilling, the City of Ames decided in 1972 to develop a resource recovery facility. The source of refuse could be guaranteed by the city and county, and the city-owned power plant could be the user of the RDF. Construction began in April, 1973, and the plant was opened in November 1975; it is the first operational RDF plant and is unique in being a small facility serving a population of only 65,000. Approximately 136 to 180 Mg/d (150 to 200 TPD) of MSW is available from the city.

PROCESS - Refuse is received on a tipping floor and is conveyed to a coarse shredder in which 45 Mg/h (50 TPH) of MSW are reduced to an average size of 15 to 20 cm (6 to 8 in.). Following the shredder is a three magnet system recovering 90 to 95% of the ferrous metals. The recovered metal goes through a second magnetic system to release trapped non-ferrous material before being sent to a storage bin. The main flow of refuse from the first magnetic system continues through a second shredder where it is reduced to a maximum size of 3.8 cm (1.5 in.). The finely shredded material is taken across a vibrating screen to remove sand and into an air classifier. The light fraction is isolated in a cyclone and passed through an airlock to a storage bin near the power plant. The heavy fraction contains marketable materials, primarily aluminum, and a separation process designed by Combustion Power Co. is in the shakedown stage. The remaining material is landfilled.

Ames power plant has three boilers, two of which have spreader-stokers that can take up to 50% refuse by fuel value with the usual coal; the third is a 33 mw suspension-fired unit also modified to accept RDF.

ECONOMICS - The capital cost of the facility was $5.6 million. Unit costs of operation and capital amortization cited by Ames (Waste Age, October 1975) are $15.71/Mg ($14.25/ton) and credits total $14.39/Mg ($13.05/ton). When operating at less than rated capacity, the facility would not enjoy such a favorable net cost of disposal.

NAME - Americology/Milwaukee RDF and Materials Recovery Plant

TYPE - RDF production and recovery of newspaper, cardboard, iron, aluminum, and glass from MSW.

DEVELOPER - Americology Division of American Can Co., Greenwich, Conn.

HISTORY - Milwaukee MSW is to be handled by American Can for a 15-year period. The facility built by Americology for processing the wastes became officially operational in May of 1977. The city has an option to buy it after the first 5 years of operation and to share in revenues from the sale of recovered products.

PROCESS - The facility can process 1089 Mg/d (1200 TPD) of MSW. Two processing lines shred the refuse to less than 38 mm (1-1/2 in.) and concentrate the organic fraction through use of air classifiers. About 60% of the raw MSW is expected to be recovered as RDF, which will be purchased by the Wisconsin Electric Power Co. for supplemental firing in suspension coal boilers. Aluminum, ferrous metals, and a glassy aggregate for use by the City's Public Works Department are also isolated.

ECONOMICS - The plant costs $18 million, including modifications at the power plant. No operating cost has been disclosed. Americology will be paid $11/Mg ($10/ton) for MSW disposal, with an escalation clause being in the contract with the city.

NAME - Hydrasposal/Fibreclaim Solid Waste Recycling Plant, Franklin, Ohio

TYPE - Wet pulping and separation of MSW

DEVELOPER - Black Clawson Co., New York City and Middletown, Ohio

HISTORY - The city of Franklin, Ohio, desired an improved method of MSW disposal in 1969 and obtained a two-thirds grant from HEW for construction of a 137 Mg/d (150 TPD) plant to demonstrate a new process developed by Black Clawson. Construction began in September 1970 and the plant was operational in June 1971. Black Clawson still operates the plant under contract to the city of Franklin.

PROCESS - The process equipment, normally handling only 36 to 45 Mg (40 to 50 tons) per day, is housed in a 1022 m^2 (11,000 ft^2) building. Refuse is received on a tipping floor and then conveyed to a 3.6 m (12 ft) diameter Hydrapulper powered with a 224 kW (300 HP) motor. Recycled water is mixed in and a 3.5% slurry is formed. Various washers, perforated plates, liquid cyclones, and screens then isolate material fractions. Long and short fibers are recovered, along with ferrous metals and glass. Dewatered non-recoverable organics and sewage sludge are burned in a fluidized bed Dorr-Oliver FluoSolids reactor. Heat recovery is not attempted because of the relatively small size of the plant.

ECONOMICS - The EPA 2nd Report to Congress lists a cost of $8.3 million for a 454 Mg/d (500 TPD) plant of this type and calculates an annual operating cost of $1.5 million. Net unit costs would be $9.75/Mg ($8.83/ton).

BIOLOGICAL CONVERSION PROCESSES

Biological processes transform organic materials by the action of living organisms. In the case of interest here, the transformation is one of organic wastes into a useful form of fuel. The principal processes for doing this include anaerobic digestion of sewage, municipal solid waste, or manure to produce methane; and hydrolysis of paper, wood or crop waste to sugar with subsequent fermentation to ethyl alcohol (ethanol).

Anaerobic Digestion

Anaerobic digestion is a natural decay process that commonly occurs at the bottom of marshes where there is no oxygen. Marsh gas, containing combustible methane, results from the decomposition of vegetable matter and bubbles to the surface. This can also occur during sewage treatment, and tank digesters were early developed to catch the gas for use in street lighting (Ref. B-36). Because the process produced a fuel gas before natural gas was available, and because it also stabilized sewage solids and reduced health hazards, the use of anaerobic digestion grew through the 1920's. Many sewage treatment plants were self-sufficient in energy and some had an excess of gas for sale (Refs. B-36, B-37, B-38). However, anaerobic digestion developed a reputation for unreliability because it can be upset by unskilled operation, equipment inadequacies, or toxic materials in the waste feed, and other processes for the disposal of sewage sludge were sought (Refs. B-36, B-38).

Interest continued in India, where methane production systems were developed for village homes based on the digestion of cow dung. These systems made fuel for light and cooking and provided a relatively sterile fertilizer in the form of digested sludge. Similar digesters are in common use on the many small pig farms on Taiwan (Ref. B-39).

Generation of methane by anaerobic digestion in the United States is being given renewed interest. Estimates have been made that 10% to 11% of the 1970 demand for natural gas could be met by methane derived from sewage sludge and municipal solid waste; in addition, if all animal and crop wastes were digested, the above figures would be doubled (Refs. B-40, B-41).

Anaerobic digestion is a wet process performed in stages by two groups of bacteria. The first group, the acid formers, liquefy the organic waste solids and convert complex organic substances such as carbohydrates and proteins to simple organic acids. The second group of bacteria, the methane producers, consume these acids and release carbon dioxide, methane, and traces of other gases (Refs. B-40, B-41). The chemistry of the process may be represented by:

$$C_6H_{10}O_5 + H_2O \xrightarrow{\substack{\text{Acid forming}\\ \text{bacteria}}} 3C_2H_4O_2 \xrightarrow{\substack{\text{Methane}\\ \text{producing}\\ \text{bacteria}}} 3CO_2 + 3CH_4$$

$$\text{Carbohydrates} + \text{Water} \longrightarrow \text{Acetic Acid} \longrightarrow \text{Carbon dioxide} + \text{Methane}$$

The mix of gases produced will vary with the type of wastes fed to the process. The following dry gas compositions have been reported:

	Sewage sludge (Ref. B-37)	Animal wastes (Ref. B-42)	Municipal solid waste (Ref. B-43)
Methane (CH_4)	65 - 70%	54 - 70%	50%
Carbon Dioxide (CO_2)	30 - 35%	27 - 45%	50%
Nitrogen (N_2)	Trace	0.6 - 3%	Not Mentioned
Hydrogen (H_2)	Trace	1 - 10%	Not Mentioned
Carbon Monoxide (CO)	Not Mentioned	0.1%	Not Mentioned
Oxygen (O_2)	Not Mentioned	0.1%	Not Mentioned
Hydrogen Sulfide (H_2S)	Trace - 0.2%	Trace	Trace

Some of these bio-gases have significantly more methane than carbon dioxide, although the chemical reaction predicts that they should be equal. This occurs because carbon dioxide is much more soluble in water than is methane, and a portion of it remains in the water required in the process.

All of these gas mixes will burn without purification, and are used directly by the sewage treatment plants and their industrial customers. Heating value of these gases is in the range of 20 to 26 MJ/m^3 (540 to 700 Btu/ft^3), provided principally by the methane which has a heating value of about 37 MJ/m^3 (1000 Btu/ft^3). Natural gas is about 98% methane and methane purified from a biogas mixture can be used directly in natural gas systems (Ref. B-42, B-44).

Virtually all organic wastes, whether municipal, industrial or agricultural, can be anaerobically digested. Some materials are easier to digest than others; gas yields from cow manure digestion, for example, ranged between 0.09 and 0.20 m^3/kg (1.4 to 3.2 ft^3/lb) of volatile solids, compared with 0.38 to 0.57 m^3/kg (6.1 to 9.1 ft^3/lb) of volatile solids in sewage sludge digestion. This has been attributed to the difficulty of breaking down the cellulose in the cow manure (Ref. B-45). The absence of toxic materials, such as sulfides, heavy metals, and toxic organic compounds is important, as is the maintenance of an oxygen-free environment.

Anaerobic digestion can take place at two optimum temperature levels, the mesophilic level, 30°C to 37.5°C (86°F to 99.5°F), and at the thermophilic level, 49°C to 51°C (120°F to 124°F). The rates of reaction at the thermophilic level are faster than those at the mesophilic level, but the heating necessary to maintain thermophilic temperature make such systems less economically attractive (Ref. B-41). The correct pH level, optimally between 7.0 and 7.2, is critical, as is the correct carbon: nitrogen: phosphorus ratio (Refs. B-41, B-44).

Because anaerobic digestion is a biological process, sufficient time must be allowed for the bacteria to function. In continuous sewage sludge digesters, organic solids retention times range between 15 and 20 days, by which time 90% digestion has been reached. With longer retention times the digestion rate becomes slower, and over 40 days retention time would be necessary to attain 95% digestion of the potentially biodegradable material (Ref. B-46).

Methane-containing biogas is created naturally in many landfills, and the release of foul smelling gas can be a major source of complaints. Several organizations have seen this gas evolution as an energy recovery opportunity and are now extracting and purifying the gas. A description of one of these methane recovery programs is given at the end of this section.

Anaerobic digestion of sewage sludge is one of the principal means for sewage treatment. Methane recovery, eclipsed for a while by the availability and low cost of natural gas, is now receiving new attention. About 0.028m^3 (one cubic foot) of biogas is generated every day for each person in the area served, so it has been recommended that large cities can best practice methane recovery (Ref. B-47). The Metropolitan Sanitary District of Greater Chicago has seven treatment plants, five of which has anaerobic digestion systems. Biogas is used for heating the raw sludge feed, maintaining digester temperature, and heating the buildings. An excess of 5% to 30% is available for outside use, and various alternatives are being explored. Energy production, after satisfying all digester heat requirements and converting excess gas produced to electrical energy, has been calculated to be twice the electrical energy required to operate the system (Ref. B-48).

The Santa Clara/San Jose Sewage Plant in California uses biogas to run large internal combustion engines, and in Orange County, California, gas turbine generators are powered by biogas (Refs. B-49, B-50). The City of Los Angeles operates the Hyperion Treatment Plant, a major facility serving a population of 3 million people. Biogas is used for generating electricity both in-house and at a neighboring generating plant (Ref. B-37).

Anaerobic digestion has also been proposed for municipal solid waste. Work done by J. T. Pfeffer for the National Science Foundation (Ref. 43) and U.S. EPA (Ref. B-41) led NSF to fund the Dynatech Corporation to develop a preliminary design and economic model for a 1000 TPD plant capable of producing approximately 104 670 m^3/d (317 x 10^6 ft^3/day) (Ref. B-51). NSF also funded a Mitre Corporation study to provide background information for an "Urban Trash Methanation Proof-of-Concept Experiment," which reviewed the state of the art in feed preparation, digestion, sludge dewatering and disposal, and gas processing (Ref. B-52). As a result of this work, an ERDA-funded facility is being built at Pompano Beach, Florida, by Waste Management Inc., and Jacobs Engineering Co. Scheduled to be operational late in 1977, the plant will have a daily capacity of 91 Mg (100 ton) of refuse (Ref. B-53).

A similar system has been proposed by D. L. Klass and S. Ghosh of the Institute of Gas Technology (Ref. B-50, B-54). In both concepts, the organic fraction, typically about 70% - 75% by wet weight of the total, is isolated from the refuse. The shredded material, principally paper, is mixed with sewage sludge and fed into an anaerobic digester. Biogas removed from the digester is processed to pipeline methane, using conventional gas cleaning technology, Sludge from the digester is treated, using conventional waste water techniques (Refs. B-54, B-55). The principal questions to be answered at the Pompano Beach facility are concerned with the amount of feed processing necessary and the operating conditions for the digester (Ref. B-52). In all such plants, an important concern will be the ultimate disposal of the sludge remaining after the digestion.

According to a 1975 cost analysis made by Dynatech, it should be possible to produce methane from solid waste and sewage sludge to sell at a price of \$0.074/m^3 (\$2.09 per thousand cubic feet) (Refs. B-43, B-51). This price includes penalties for disposal of process wastes and credits for disposal of wastes input to the process (\$11.74/Mg or \$10.65/ton). The process has been criticized as being inefficient because only 35% of the energy content of the solid waste is recovered as methane and when a penalty is taken for the energy needed to run the process, an overall energy efficiency of 25% results (Ref. B-55). The process still produces 2.67 times more energy than is required to run it, however. In balance, the process is marginally expensive and requires further development, but could be attractive where waste disposal charges are high and methane is in short supply. Additional work on generation of methane from garbage and sewage is being conducted at the University of Arizona (Ref. B-36).

Digestion of animal wastes to obtain methane is receiving increased attention in the U.S. B. A. McDonald has designed and operated a prototype dairy cow manure digestion system for over a year (Ref. B-56) and the Ecotope Group has prepared a technical and economic feasibility study of anaerobic digestion for the Washington State Honor Farm (Ref. B-42). Most of these developers have been concerned with systems for small farms of under 400 cows, although Fry and Taiganides (Ref. B-44, B-57) have performed work with farms with several thousand hogs. Increased confinement of cattle in feedlots has sharply increased the availability of manure in recent years, while at the same time the use of manure for fertilizer has virtually ceased. New EPA regulations on pollution from feedlot operations and the shortage of natural gas have combined to make the production of methane by anaerobic digestion attractive (Ref. B-37). Calorific Recovery Anaerobic Process Inc. and ERA Inc. have signed contracts with a pipeline subsidiary of Peoples Gas Co. of Chicago for $18.4 \times 10^6 m^3$ and $18.1 \times 10^6 m^3$ (650 and 640 million cubic feet) of methane respectively (Refs. B-38, B-58, B-59). The Federal Power Commision has approved a price of \$0.047/m^3 (\$1.33 per thousand cubic feet) that the pipeline company will pay Calorific (Ref. B-60). Bio-Gas of Colorado, has issued a prospectus for a 5000 cow unit anaerobic fermentation facility (Ref. B-61), and Jacobs Engineeering Co. states that they are helping a feedlot operator develop a total manure recycling system that produces methane, fishmeal, and cattle feed. Research has been started or expanded at a number of universities, including Cornell (Ref. B-62), Missouri (Ref. B-63), and Wisconsin (Refs. B-64, B-38).

Anaerobic digestion of manures is essentially the same as that for sewage treatment, the most important difference being that cattle manures are more difficult to digest and produce less gas than sewage. This is because about 10% of a feedlot steer's diet, or 50% of a dairy cow's diet, is roughage that is hard-to-digest cellulose and because manure has already essentially been through an anaerobic process. Yields from MSW are similarly low because of the cellulose fraction.

The volume of gas produced per pound of volatile solids (VS) added and the percentage methane in the gas varies according to the material being digested. Some representative figures from laboratory experiments are given below (Ref. B-44).

	Proportion	Gas Produced		% Methane
Steer Manure	100%	0.087 m^3/kg VS	1.4 ft^3/lb VS	65.2
Steer Manure & Chicken Manure	50% 50%	0.212	3.4	61.9
Chicken Manure	100%	0.312	5.0	59.8
Newspaper & Sewage Sludge	10% 90%	0.618	9.9	67.1

While anaerobic digestion is capable of significantly reducing the volume and biological activity of organic wastes, disposal of large quantities of supernatant digester liquid and the final sludge remains a major problem. In sewage treatment, the supernatant is recycled through the waste water treatment, and the sludge has been either ocean dumped or dewatered and landfilled. More extensive recycling programs have been proposed for manure digester residuals. The supernatant is an ideal feed for an algae pond in which small food fish can be grown for use as cat food or a cattle feed supplement. The digested sludge is an excellent fertilizer that contains all of the nutrient value of manure but is odor free and not attractive to flies and other pests; it may also be possible to make a cattle feed supplement from the dewatered sludge (Ref. B-61, B-62).

Fermentation

Alcohol (ethanol) produced by fermenting sugars with yeast can be used as a fuel. Wastes suitable for making ethanol contain cellulose, a principal material in plants, which must first be converted to sugar by hydrolysis. Following fermentation of the sugar, the resulting alcohol must be concentrated by distillation. The process of producing ethanol from waste therefore, requires three independent major steps:

$$\text{Cellulose or Carbohydrates} \xrightarrow{\text{Hydrolyze}} \text{Sugar} \xrightarrow{\text{Ferment}} \text{Dilute Ethanol} \xrightarrow{\text{Distill}} \text{Concentrated Ethanol}$$

All of these are ancient processes whose most familiar combined use is the production of beverage liquor. About 1830, the development of continuous process column still made it possible to produce large quantities of ethanol, and it began to replace whale oil as a fuel in lamps (Ref. B-65). Slightly earlier, a major advance in hydrolysis was made when it was found that wood and other cellulosic materials heated with a strong acid would be converted to sugar. Traditionally, however, industrial fermentations used molasses and sugar processing residues which were readily available and did not require hydrolysis (Ref. B-66).

In the early days of the automobile, alcohols were given serious consideration as motor fuels before being displaced by gasoline. In some European countries, a shortage of gasoline was relieved by blending it with as much as 30% alcohol (Ref. B-65). During World War II, acid hydrolysis, fermentation, and distillation to produce fuel were investigated in Germany and by the U.S. Forest Products Laboratory (Ref. B-67). About this time an alcohol plant capable of producing 53 m^3/d (14,000 gallons per day) of 95% ethanol from lignosulfonate chemicals left over from paper making was built at Georgia-Pacific's Bellingham Division Plant (Ref. B-68). Following the war, the production of ethanol from ethylene in petrochemical plants became more economical than the hydrolysis/fermentation process. The Georgia-Pacific Plant is believed to be the only one of its type remaining in the United States, excluding alcoholic beverage producers, who cannot by law use synthetic alcohol in their products.

Wood is composed of about 25% lignin and 75% cellulose chains. Hydrolysis, either with acid or enzymes, breaks apart the lignin and cellulose chains, and then further reduces the cellulose to various sugars. Chemically, the reaction can be generally represented as:

$$(C_6H_{10}O_5)n + nH_2O \xrightarrow{\text{Acid}} nC_6H_{12}O_6$$

$$\text{Cellulose + Water} \quad = \quad \text{Glucose}$$

Only about 70% of these sugars are readily fermentable, however, so that only about 52% of the wood can be converted to alcohol - a major limitation on the process (Ref. B-69). The sulfite pulping process used by Georgia-Pacific's Bellingham Division is similar to sulfuric acid hydrolysis, except that it is limited to separating the cellulose chains and sugar production is minimized. The cellulose becomes paper and the fermentable sugars, amounting to a small fraction of those potentially available from the cellulose, are made into alcohol. Yield is about 0.027 m^3 of ethanol per Mg of wood (6.5 gallons per ton) (Ref. B-68).

Since the mid-1960's, a new hydrolysis process based on enzymatic action has attracted attention. The principal developers have been the U.S. Army Natick Laboratories, whose original goal was to prevent biological decay of textiles. They found (Refs. B-70, B-71) that the fungus Trichoderma viride was especially capable of producing enzymes for breaking cellulose down into glucose sugar, and have developed pre-pilot plant facilities handling 454 kg (1,000 pounds) of cellulose per month to investigate the operating parameters.

Acid hydrolysis is a well-developed technology while enzyme hydrolysis is still in the research stage. Contact time for the enzyme hydrolysis is 50 hours at 50°C (122°F) compared to 5 hours at 150°C (302°F) for acid hydrolysis, and the feed material for enzyme hydrolysis must be finely ground to achieve this rate (Ref. B-66). However, there exists a potential for higher yields of fermentable sugars from enzyme hydrolysis than from the acid process, and further development work is continuing (Ref. B-46).

Conversion of the fermentable sugars to ethanol follows the classic process using Saccharomyces cerevisiae yeast. The chemical reaction is:

$$C_6H_{12}O_6 \xrightarrow{\text{Yeast}} 2C_2H_5OH + 2CO_2$$

$$\text{Glucose} \quad = \quad \text{Ethanol + Carbon Dioxide.}$$

At the Georgia Pacific Plant, seven interconnected 379 m^3 (100,000 gallon) fermentors are used, with a residence time of 15 to 20 hours (Ref. B-73). About 95% of the available glucose can be converted. While the yeast can tolerate up to 15-16% alcohol by volume before being destroyed, the Georgia Pacific process consumes dilute sugar solutions and does not reach high alcohol concentrations; the yeast is recovered by centrifuging.

Fermentation can be applied to other wastes that contain or can be converted to sugar. Black Clawson Fiberclaim Inc. is investigating the use of its Hydrapulper to prepare the cellulose fraction of municipal solid waste for conversion to ethanol (Ref. B-73). Kraftco produces alcohol and vinegar by fermenting lactose from cheese whey. Fermentation has not become more popular because (1) there are other means for recycling these wastes at least as economically attractive, and (2) high degree of government regulation of alcohol production facilities (Ref. B-65).

No industrial hydrolysis/fermentation alcohol plants have been built since the second war, so available cost data are old. A number of re-estimates have been made, producing total cost figures of \$0.08 to \$0.25/dm^3 (32¢ to 94¢ per gallon) of ethanol from solid waste using the acid hydrolysis process (Ref. B-66, B-69, B-74, B-75). Estimates for a plant using enzyme hydrolysis would be on the order of 50% higher (Ref. B-71, B-46).

The use of alcohol as a fuel, especially in vehicles, is fairly well known, but the technology needs to be up-dated. Currently, the State of Nebraska is involved in a two million mile test using 36 vehicles from the Department of Roads burning a mix of 10% ethanol and 90% gasoline. Preliminary results indicate the possibility of running more miles per unit of fuel, but this may be offset by the higher price of the blend (Refs. B-76, B-77, B-78). United International Research, Inc. has developed Hydrofuel II, a mixture of 60% gasoline, 30% ethanol, 10% water, and proprietary chemical called Hydrelate. Advantages claimed for Hydrofuel II are an increase in octane number and a decrease in nitrogen oxide emissions (Ref. B-79).

Descriptions of Key Projects

Brief descriptions of two biological projects are presented on the next pages.

NAME - Sanitary Landfill Methane Recovery Program, Los Angeles

TYPE - Methane recovery from landfill. At the Palos Verdes Landfill approximately 28 300 m^3 (1 million cf) of purified methane are recovered daily.

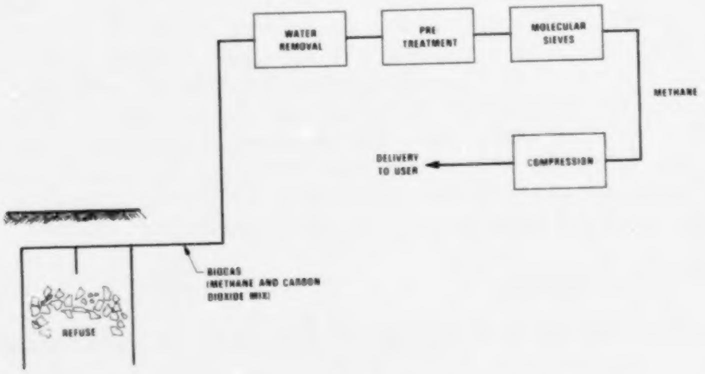
DEVELOPER - NRG NuFuel Company, a joint venture of NRG Incorporated, Phoenix, and Reserve Oil and Gas Co., Los Angeles; now called Reserve Synthetic Fuels.

HISTORY - The main 696 084 m^2 (172 acre) Palos Verdes Sanitary Landfill, owned and operated by the Los Angeles County Sanitation Districts, was started in 1963. Decomposition of refuse in the landfill created biogas that migrated to the surface, causing an unpleasant odor. Sanitation Districts' engineers installed wells and burners to collect and flare the gas. In October 1973, the Sanitation Districts signed an agreement with NRG for the recovery and sale of methane from the biogas. The present processing facility was started in February 1975 and became operational with five wells in June 1975.

PROCESS - The decomposition of refuse in landfills produces biogas, a mixture of roughly equal parts of methane and carbon dioxide. The biogas production potential of a landfill depends on many factors. To qualify for the Reserve program, the landfill must contain at least 1.8 Tg (2 million tons) of refuse in place, a minimum depth of 12.2 m (40 ft), a high percentage of decomposable organic material with adequate moisture content, a suitable type of cover, and close proximity to energy markets.

To tap the biogas, wells are drilled into the landfill. Biogas is withdrawn from the landfill. Biogas is withdrawn from the landfill under vacuum through an underground collection system and pretreated to remove moisture, hydrogen sulfide, and other trace contaminants. The gas is then passed through molecular sieves, which selectively remove the carbon dioxide, leaving clean, dry pipeline quality methane (natural gas). The methane is compressed to specific pipeline requirements for delivery to the user. In the case of the Palos Verdes Landfill, enough recovered methane to meet the daily energy needs of 3500 homes goes directly into the distribution system of the Southern California Gas Company.

ECONOMICS - Cost and revenue data are the proprietary information of the company. The company's descriptive brocure states that royalty revenues of 12-1/2% of gross sales could be paid to the landfill owner.



NAME - RefCOM (Refuse Conversion to Methane), Pompano Beach, Florida

TYPE - Experimental anaerobic digestion facility for studying controlling parameters for converting MSW to methane.

DEVELOPER - Dr. John T. Pfeffer, University of Illinois, Consultant; Jacobs Engineering, engineering/construction; Waste Management, Inc., prime contractor.

HISTORY - As discussed within Appendix B, anaerobic digestion of sewage to methane has been practiced for many years, but conversion of refuse in a similar manner has only been studied on a laboratory scale. To establish the factors affecting the ultimate commercial feasibility of such a process, ERDA has contracted to Waste Management, Inc., for the design and operation of an experimental facility. Construction began in February 1977 and is scheduled to be completed by the end of 1977.

PROCESS - Approximately 85m^3 (3000 ft^3) of methane is expected to be produced from each 0.9 Mg (1 ton) of processed MSW; the facility is designed for a capacity of 90 Mg/d (100 TPD). The organic fraction of MSW will be enriched and then mixed with primary sewage sludge before anaerobic digestion is initiated in large tanks. Design features for variable adjustments have been incorporated into the plans.

ECONOMICS - The facility has a cost of $2.8 million, but the plant being of an R&D nature, this value cannot be used to establish eventual commercial costs.

THERMAL/CHEMICAL CONVERSION PROCESSES

Overview

The energy content of wastes is most typically utilized by the exothermic direct and complete oxidation to the elements and oxides (combustion, as described in the following Section). An alternative method involves the preparation of new fuels through conversion of the rather large number of high molecular species in the waste to a relatively few low molecular weight compounds plus oftentimes a solid residue of high carbon content. The new materials require energy for their formation and a kg of total products will possess a heating value less than the same mass of starting materials. While isolatable fractions can be obtained having a higher heats of combustion per unit weight than the original average reactant mixture, this is achieved at the expense of other fractions having low, or zero, heating values. The loss in energy is tolerated because of (1) the convenience of the physical or chemical form of the new fuel or (2) the reduced volume of total gases over that formed in a typical incineration process, and hence lower capital investment and air pollution control costs.

The conversions can be accomplished through chemical or thermal processes. The methods can yield essentially any fuel form desired, or can be used to synthesize compounds such as ammonia, which otherwise would have consumed fossil fuels in their normal commercial production. This project is limited to the following:

- The gaseous, liquid, or solid mixtures resulting from thermal decomposition schemes with no oxygen present or only sufficient to create heat to drive the reactions (pyrolysis).
- Reactions designed to give high yields of synthesis gas or "syngas" (hydrogen-carbon monoxide mixtures).
- Use of carbon monoxide, hydrogen, or water as direct reactants with waste materials.
- Chemical conversion of thermal decomposition products to methanol, methane, or ammonia.

The publications in the technology area range from those dealing with theoretical considerations such as the mechanisms and kinetics of decomposition of cellulose, through detailed compositional analysis of the products from laboratory scale reactors, to descriptions of start-up experiences of plants processing as much as 900 Mg (1000 tons) of waste per day. Investigators include scientists and engineers from government, university, and industrial organizations. Advances in the field are undoubtedly occurring more rapidly than in any other waste-to-energy R&D technology. With the potentiality for processing all forms of organic wastes (municipal, industrial, sewage, animal, and agricultural) to numerous fuel types over a broad range of input capacities, several of these systems will undoubtedly enjoy a moderate degree of commercialization in the next five years.

The reaction conditions of temperature, pressure, heating time, and relative reactant quantities can be varied to optimize the yield of a particular type of fuel or synthesis gas. The actual chemistry involved is complicated because of the large number of simultaneous reactions that may occur, with each being influenced by the extent of equilibrium of the other. Measurement of the composition and properties of the final mixture is simple, however, and research tends to be highly empirical. The principal reactions involved include the following:

Drying Zone

$$\text{Solid Waste} + \text{Heat} \rightarrow \text{Dry Waste} + H_2O \tag{1}$$

Pyrolysis Zone

$$\text{Dry Waste} + \text{Heat} \rightarrow C + CO_2 + H_2O + \text{Hydrocarbons} + H_2 + CO \tag{2}$$

Oxidation and Reduction Zones

$$C + O_2 \rightleftarrows CO_2 + \text{Heat} \tag{3}$$

$$C + CO_2 + \text{Heat} \rightleftarrows 2CO \tag{4}$$

$$C + H_2O + \text{Heat} \rightleftarrows CO + H_2 \tag{5}$$

$$C + 2H_2 \rightleftarrows CH_4 + \text{Heat} \tag{6}$$

$$2C + O_2 \rightleftarrows 2CO + \text{Heat} \tag{7}$$

$$CO + 3H_2 \rightleftarrows CH_4 + H_2O + \text{Heat} \tag{8}$$

$$CO_2 + H_2O \rightleftarrows CO_2 + H_2 + \text{Heat} \tag{9}$$

$$H_2 + 1/2O_2 \rightleftarrows H_2O + \text{Heat} \tag{10}$$

$$CO_2 + 4H_2 \rightleftarrows CH_4 + 2H_2O + \text{Heat} \tag{11}$$

$$2CO + 2H_2 \rightleftarrows CH_4 + CO_2 + \text{Heat} \tag{12}$$

$$CO + H_2 + \text{Organics} \rightleftarrows \text{Misc. Liquid, Solid and Gaseous Organics} \tag{13}$$

Synthesis Routes from Syngas

$$CO + 3H_2 \rightarrow CH_4 + H_2O + \text{Heat} \tag{8}$$

$$CO + 2H_2 \rightarrow CH_3OH + \text{Heat} \tag{14}$$

$$N_2 + 3H_2 \rightarrow 2NH_3 + \text{Heat} \tag{15}$$

Pyrolytic Gasifiers

With Sections 6, 7, and 8 are presented details of three pyrolytic conversion systems (Georgia Tech, Torrax, and Purox) where the temperature and duration of exposure of the organic waste material have been adjusted to produce significant yields of gases. That the end energy forms from each is quite different in spite of the basic same shaft reactor being used in all cases is indicative of the versatility of this type of processing.

The mobile agricultural pyrolysis system being developed by the Engineering Experiment Station (EES) of the Georgia Institute of Technology (Ref. B-80) must be independent of outside power. The low heating value gas produced is therefore totally consumed as a fuel for an internal combustion engine driving an electrical generator and for a combustor whose hot oxidized gases are used for drying incoming wastes. The liquid and solid products of pyrolysis are mixed for sale as a consumer fuel.

The Torrax gasifier (Ref. B-81) produces its necessary heat by air oxidation of char as does the EES system. The combustion air in this case has been preheated in an exchange system and temperatures in the oxidation zone are sufficiently high to melt the inorganic waste fraction to a slag. The hot combustion gases then pass over essentially dry wastes and decompose them to a gas mixture that leaves the reactor at approximately 427°C (800°F) and still contains organic particulate matter. Rather than lose the sensible heat and expend energy in cleaning up the stream, the reactor off-gas is immediately combusted and the heat used to generate steam.

Because there are broad applications for a fuel and synthesis gas, the Union Carbide Corporation has developed its Purox pyrolysis system to yield a medium-level heating value gas capable of being pipeline transported (Ref. B-82). This is accomplished by using gaseous oxygen in the char combustion zone, and thus the pyrolytic gases are not diluted with nitrogen. The gas, having a heating value of approximately 14.57 MJ/Nm^3 (370 Btu/SCF) can serve directly as a utility fuel. It is also capable of serving as the feedstock for synthesis of a wide range of compounds, including methane, methanol, and ammonia. Such conversions are discussed in Appendix C.

While the three candidate systems selected for engineering analysis are among the most advanced pyrolytic gasifiers now available, a number of other investigators have been active in this field. The largest waste gasifier yet constructed is the Monsanto Landgard system in Baltimore (Ref. B-83). It was designed to process 907 Mg/d (1,000 TPD) of MSW by partial air oxidation in a rotary kiln to yield a gas having an HHV of 3.88 MJ/Nm^3 (98.5 Btu/SCF). The gas was then to be immediately combusted to produce steam in a waste heat boiler, which is then used for cooling and heating purposes. The plant has experienced particulate emissions in excess of state regulations and mechanical problems in the kiln; it is presently undergoing modification.

Battelle Northwest (Ref. B-84) has developed a gasifier patterned after fixed bed coal systems that use a vertical shaft with air combusting the char in the presence of steam. Feed of approximately 1 Mg/d was introduced through a rotary air lock. Temperatures at the grate were 810 to 1,080°C (1,490 to 1,976°F), and the HHV of the off-gas was about 6.06 MJ/Nm^3 (154 Btu/SCF).

Battelle has also investigated (Ref. B-85) the use of molten sodium carbonate as the heating media for the gasification of MSW. At 900°C (1,652°F), a gas was obtained having an HHV of 19.69 MJ/Nm^3 (500 Btu/SCF).

Barber-Colman (Ref. B-86, B-87) developed, in a pilot unit, a unique pyrolysis system that involved radiant heating with hot overhead tubes in a horizontal retort. No commercial equipment was ever built. In the concept the refuse is fed by screw-conveyor into the sealed unit onto a lead bath kept molten by the heat from the radiating tubes. The liquid lead, flowing in a channel along the length of the retort, carries the pyrolyzing organics. At the exit end, char and ash are scraped off the lead, which in turn is pumped back to the pyrolysis retort. The rapid heat transfer to the refuse from the lead results in a range of hydrocarbons. The composition of the product gases were reported (by volume) as 16.4% H_2, 29.4% CO, 18.4% CO_2, 23.3% CH_4, 3.4% C_2H_4, 0.5% C_2H_6, 7.9% C_6H_6, 0.6% C_7H_8; the HHV was 30.32 MJ/Nm^3 (770 Btu/SCF). The cooled gas, with the C_6 + condensed out, has a composition of 18% H_2, 32% CO, 20% CO_2, 25.5% CH_4, 0.5% C_2H_6, with an HHV of 19.30 MJ/Nm^3 (490 Btu/SCF).

For the past several years, Pyrotek (Ref. B-88) has been developing a fuel gas producer using a pyrolysis unit fed by shredded refuse. The unit under test is at the bench level and essentially hand fed. The community of Riverside, California, is purportedly allowing Pyrotek to build a small demonstration unit in their city (with Pyrotek funds) to test its feasibility. The laboratory system is a horizontal reactor fed by hand with the shredded refuse conveyed internally by a vibrating conveyor and heated by hot radiant tubes above the moving bed. These tubes have been heated electrically, but they expect that approximately one-third of the pyrolysis gas will be used in a commercial unit for heating. The gases are scrubbed to remove acid gases, oil, and solid particulate matter. The volumetric composition of the gas is 19% H_2, 18% N_2, 26% CO, 13% CH_4, 18% CO_2, and 4% C_2H_4, with an HHV of 13.78 MJ/Nm^3 (350 Btu/SCF).

In other reported work, the Urban Research and Development Corporation (Refs. B-87, B-89) investigated a vertical shaft slagging furnace, using preheated combustion air and yielding a gas having an HHV of 6.26 MJ/Nm^3 (159 Btu/SCF); West Virginia University (Ref. B-90, B-91, B-92) has studied the concept of a fluidized bed gasifier operating at 810°C (1,490°F) and producing a gas having an HHV of 16.42 MJ/Nm^3 (417 Btu/SCF); Texas Tech University, in a series of studies on energy forms, including ammonia, from cattle manure (Ref. B-93, B-94, B-95, B-96), has examined experimental conditions best suited for energy recovery from this abundant waste; and the U. S. Bureau of Mines (Refs. B-97, B-98, B-99), in the gasification phase of their wide-ranging studies on waste conversion processes, has obtained gases having an HHV as high as 21.46 MJ/Nm^3 (545 Btu/SCF).

Pyrolytic Liquefaction

In the pyrolysis process, thermal energy is used to break the chemical bonds of large molecular species, yielding fragments and additional products of reaction. As the temperature to which the original (and typically solid) material is exposed increases, the rate of decomposition increases, as does the portion of the total products that are gases. At lower temperatures, fragmentation occurs to a molecular size such that, after cooling, liquid products predominate. Rapid quenching from the pyrolytic temperature to a temperature where the liquid product is thermally stable is essential to recovery of significant yields of potentially useful liquid fuels. Because of the more exacting nature of process development for liquids, little totally pyrolytic R&D towards such products has been reported. The only process to yet reach demonstration scale is the Occidental Flash Pyrolysis system, now undergoing start-up tests in a 181 Mg/d (200 TPD) plant; it is described in detail in Section 9 and has been optimized to yield an oil. The Georgia Tech system happens to operate under temperature-time conditions to produce a significant fraction of a liquid product; it is described in Section 6. Liquid fuels have significant advantages and further research should be conducted for developing economical new pyrolytic liquefaction systems.

Work now in progress (Ref. B-100) at the Naval Weapons Center, China Lake, California, indirectly produces a liquid fuel after an initial pyrolysis step. Finely divided cellulosic waste is carried by a gas through a hot zone at 760°C (1400°F) and the products rapidly quenched. Approximately 35 to 40 percent of the solid waste energy is converted to "gasoline precursors," various olefins that could be used as a feedstock for making so-called polymer gasoline. Tests have been made by the Navy on straight ethylene as a feed to a thermal polymerization reactor and 60 percent conversion to liquids have been obtained per pass. Unleaded samples of the product has an octane rating of 90. Purification of the crude pyrolysis off-gas mixture and conversion of the lower olefins to liquids in the boiling point range of gasoline has not yet been attempted.

Chemical Reagent Systems

The pyrolytic process involves a complex decomposition mechanism and interaction of various compounds to form new products; it could be generally characterized as a thermal process where no external reagents are deliberately added. Such additions can permit an even wider range of products to be formed and these can be "tailored" to particular forms by the greater degree of control offered by the techniques of modern chemical synthesis.

The case where a primary product is first obtained by pyrolysis and then chemically modified is discussed in Appendix C, where syngas from the Purox system is used as an example of a starting material. Carbon monoxide and hydrogen are the fundamental reagents for industrial synthesis and gaseous, liquid, and even solid fuels could be prepared if so desired. The gas mixtures from pyrolysis are not ideally suited for this chemistry and experiments must be conducted before accurate economics for the cost of waste-derived fuels can be established.

Appell et al (Refs. B-101, B-102) have reported on portions of the R&D on chemical conversion of different cellulosic wastes undertaken by the Bureau of Mines of the U.S. Department of the Interior. Sawdust, bark, corncobs, bovine manure, sewage sludge, and MSW have been made into heavy oils through high pressure and temperature reaction of syngas or carbon monoxide and water. Conversion of more than 90 percent of the inorganic-free wastes were obtained, with 40 to 60 percent of the products being oil. The temperature range examined was 250° to 425°C (482° to 707°F) and pressure were between 10.34 and 20.68 MPa (1500 to 3000 psi). The effects of various catalysts and operation in the presence of high boiling oils on yields and product characteristics have been investigated. The boiling point range of the products obtained have been on the order of 175° to 500°C (347° to 932°F) and the viscosities vary from readily pourable liquids to solids. Typical analyses and heating values are as follows:

	Reaction Temp.		Analysis, Wt-%				HHV		
Waste Feed	°C	°F	H	C	N	S	O	MJ/kg	Btu/lb
MSW	360	680	9.9	75.1	1.4	0.1	13.5	36.19	15,560
Hardwood	300	572	7.0	72.5	0.1	0.1	20.2	33.45	14,380
Manure	425	797	10.2	83.4	4.6	0.1	1.7	39.98	17,190

Friedman et al (Ref B-103), in a very preliminary economic analysis of the BuMines work, estimates that a city having a population of 300,000 or a cattle feedlot having 200,000 cattle could just break even on the operation of a conversion plant. This is based on an oil yield of 2 barrels/ton of dry organic wastes and a 20 year amortization of the investment.

Feldman, also an investigator for the Bureau of Mines, has patented (Ref. B-104) and reported on (Ref. B-105) the conversion of wastes to pipeline quality gas. The work is based on analogous studies on the hydrogasification of coal and lignite, and involves the reaction of cellulosic materials with hydrogen at temperatures of 500° to 670°C (932° to 1238°F) and pressures of 6.89 to 20.68 MPa (1000 to 3000 psi). Only limited feasibility test have been conducted, of which these at 650°C and 1 hour are typical:

	Test 1	Test 2	Test 3
Synthetic MSW, g	10	20	80
H_2 charge, moles	0.87	0.87	0.46
Conversion of carbon to gas, %	60.0	66.4	45.8
Conversion of carbon to hydrocarbons, %	43.4	49.7	23.3
Conversion of carbon to CO, %	8.0	5.0	8.0
Conversion of carbon to CO_2, %	8.8	11.5	14.6
Gas analysis, vol-%, H_2O and CO_2-free			
H_2	80.9	68.8	25.3
N_2	2.0	1.5	0.8
CO	3.0	3.1	1.0
CH_4	12.1	23.0	71.1
C_2H_6	2.0	3.6	1.0

Descriptions of Key Projects

Five thermal/chemical projects are briefly described on the following pages.

NAME - "Landgard" Pyrolysis System

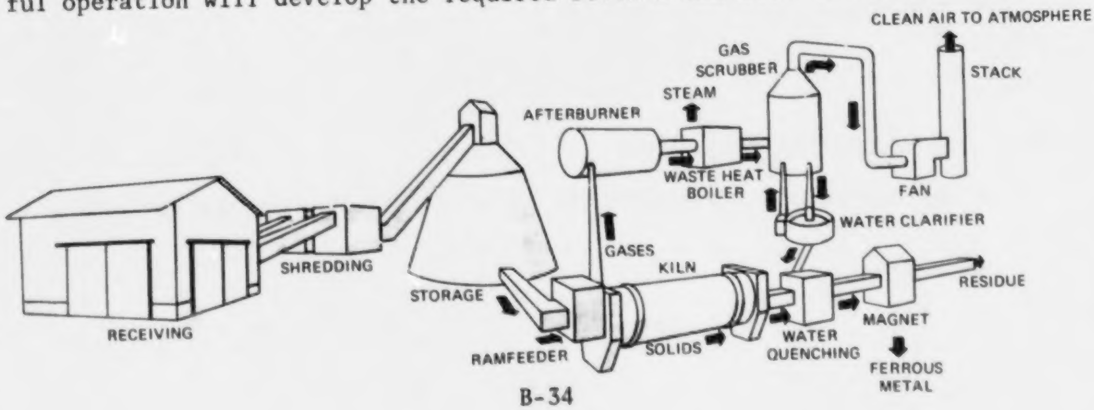
TYPE - Medium temperature, non-slagging, rotary kiln pyrolysis system using air and supplemental fuel, and recovering steam, glass, ferrous metals, and ash.

DEVELOPER - Monsanto Enviro-Chem Systems, Inc., St. Louis, MO

HISTORY - Monsanto began investigating waste resource recovery in 1967, and selecting the rotary kiln pyrolysis system. A 31.7 Mg/d (35 TPD) pilot plant was operated from June, 1969 to late 1971. In September, 1972, the City of Baltimore was given an EPA demonstration grant to help fund a 907 Mg/d (1000 TPD) "Landgard" system. Construction was from January, 1973, to February, 1975. While the pilot plant met the Maryland air pollution limits of 0.07 g/Nm^3 (0.03 gr/SCF), the full-size plant so far has not. Mechanical problems (primarily with the refractory insulation) have also been experienced. Monsanto has withdrawn from the project and the city is making efforts to correct the problems.

PROCESS - Refuse is dumped into a pit, conveyed to two shredders, and then stored in a 1814 Mg (2,000 ton) capacity bin. Shredded refuse is fed into the reactor, which is 5.8 m (19 ft) in diameter, 30.5 m (100 ft) long, and rotates at 2 rpm. During its journey through the kiln the refuse is pyrolyzed to a gas and char. The heat is provided by partial burning of the gas and char and by supplemental oil. Residue temperature is kept below 1093°C (2000°F) to avoid slagging; the off-gas is controlled to 649°C (1200°F) The off-gases move counter-current to the refuse, leaving the kiln at the feed end and going into an afterburner where they are burned with air. Two parallel boilers generate 90 720 kg (200,000 lb) of steam per hour at 2.38 MPa (330 psig) and saturated conditions, and gases are cleaned in a wet scrubber. Residual char is landfilled and ferrous metals are recovered. An overall net conversion efficiency (steam energy/refuse energy) of 42% is obtained.

ECONOMICS - The capital cost of the plant is now somewhat in excess of $20 million, which leads to a capital cost per Mg of $6.12 ($5.55/ton). Estimated operating costs if the plant were operating normally are $8.38/Mg ($7.60/ton). In 1975 it was estimated the plant could break even without a drop charge, but this is considered to be quite optimistic and only successful operation will develop the required revenue and cost information.



NAME - Georgia Tech Mobile Pyrolysis System

TYPE - Low temperature air blown pyrolysis system producing char and oil.

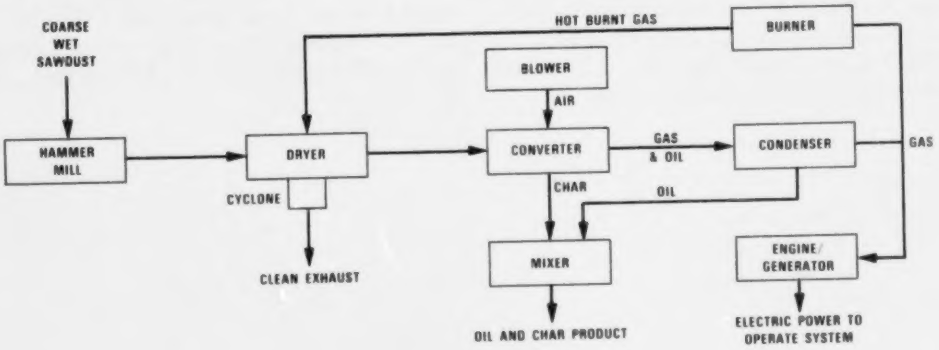
DEVELOPER - Georgia Tech Engineering Experiment Station, Atlanta, Georgia 30332.

HISTORY - Studies began in 1967 to develop an alternative to incineration for disposing of agricultural wastes such as peanut hulls and sawdust. Four experimental systems ranging in size from 5.4 to 22.7 Mg/d (6 to 25 TPD) dry input weight have been run. In addition, a 45.4 dry Mg/d (50 TPD) demonstration plant built by the Tech-Air subsidiary of American Can Co., a licensee, has been operated at Cordele, Georgia, for three years on sawdust. A preliminary design for a 91 Mg/d (100 TPD) dry feed weight mobile system to fit on two trailer units has been developed under an EPA grant.

PROCESS - Waste is fragmented to 2.5 cm (1 in.) and then dried to 10% moisture. The dried waste enters the converter through an airlock and is pyrolyzed as it descends, with partial combustion air provided through a rotating mixing arm. The desired end product is char, so pyrolysis temperatures are kept low, between 426-760°C (800-1400°F). Gases and oil vapors are taken out through a condenser to remove the oil, which can be mixed with the char in the ratio of 60% char and 40% oil to produce a dry flowing fuel with a heating value of 27.9-32.6 MJ/kg (12,000-14,000 Btu/lb). The pyrolysis gases are used to run an engine-generator to operate the system, and to fuel a burner to provide hot gas for drying the feed waste.

This system will produce approximately 225 kg/Mg (450 lbs/ton) of oil and char from 50% moisture waste. The system is designed for use with cellulosic agricultural wastes: pollution can be adequately controlled by burning the gases in the burner and using cyclones to collect dust.

ECONOMICS - The developers made a cost analysis for a 91 dry Mg/d (100 TPD) mobile system operating 250 days per year. A disposal charge of $3.30/Mg (3.00/ton) of wet waste was assumed along with a product sales price of $38.60/Mg ($35.00/ton). With their $405,000 assumed capital costs, an annual net profit of some $300,000 was calculated. Even under more conservative assumptions given in Section 6 (including $800,000 capital costs), Parsons concludes the system can be economically attractive.



NAME - Andco-TORRAX Solid Waste Energy Conversion System

TYPE - High temperature slagging pyrolysis using pre-heated air and producing steam and slag.

DEVELOPER - Andco, Incorporated, Buffalo, New York

HISTORY - Torrax Systems Inc. was created in 1969 by Andco Incorporated and the Carborundum Company. Under EPA sponsorship, a 68 Mg/d (75 TPD) demonstration plant was put into operation in 1971. Since the summer of 1972, this plant has operated as a development facility. Various waste types, including sewage, oil PVC plastic, and tires were tried in combination with MSW. In early 1976, Andco acquired all of the licensing rights to the process. A 181 Mg/d (200 TPD) plant in Luxembourg reached the start-up phase in late 1976. A 113 Mg/d (125 TPD) plant in Grasse, France, and a 181 Mg/d (200 TPD) plant in Frankfurt, Germany, are under construction.

PROCESS - Andco-TORRAX is a high temperature pyrolysis system, schematically shown in Figure 23, that reduces wastes to slag and hot gases. The gases are immediately burned and passed through a boiler to generate steam.

MSW is dumped into a storage pit and transferred by an overhead crane to the top of a cylindrical gasifier. The refuse descends through the drying, pyrolysis, and primary combustion zones. The remaining char is burned with pre-heated air and forms an inert slag with the inorganic materials. The gases are taken from the gasifier to the secondary combustion chamber at 427-538°C (800-1000°F), are mixed with the minimum air necessary for complete combustion, and burned to produce temperatures of 1204-1260°C (2200-2300°F).

Approximately 15% of the combustion gases are used in two regenerative towers to pre-heat the primary combustion air to 1093°C (2000°F). The remaining gases are passed through a boiler to produce steam. The Luxembourg facility produces approximately 2.46 units of steam per unit of refuse input at 3.45 MPa (500 psi) and 385°C (725°F) to be used for generating electricity. The cooled combustion gases are cleaned by an electrostatic precipitator and exhausted through a short stack.

The conversion efficiency of the process (energy in the output steam divided by the amount of energy in the input refuse) is 71.3%. The net thermal efficiency (energy in the steam less the steam energy required to produce the required electric power, divided by the sum of all the input energies) is 52.7%.

ECONOMICS - For a 900 Mg/d (1000 TPD nominal) plant, capital costs in 1976 dollars are estimated to be $34,600,000. Annual operating costs are $2,740,000. Unit costs would be $21.75/Mg ($19.73/ton) of refuse input and at a charge of $4.36/Mg ($1.97/1000 lb) for steam and refuse drop charge of $11.00/Mg ($10.00/ton), the plant can break even.

NAME - Union Carbide PUROX Pyrolysis System

TYPE - High temperature slagging pyrolysis system using oxygen to produce a combustible gas. Magnetic metals recovery is recommended, with other materials recovery being optional.

DEVELOPER - Union Carbide Corporation, New York, N.Y.

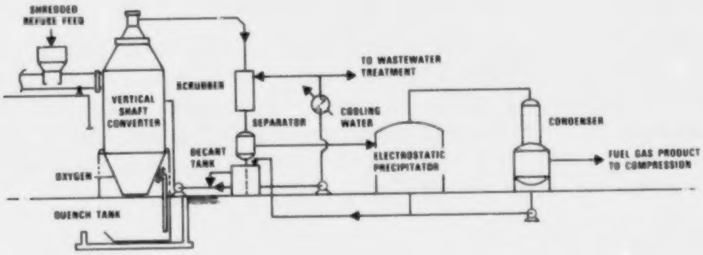
HISTORY - Development began in 1967. A 4.5 Mg/d (5 TPD) pilot plant was built in Tarrytown, N.Y., in 1970 and tested for three years. A 180 Mg/d (200 TPD) demonstration plant was built in South Charleston, W. Virginia, in 1974 and is still operating. It is considered to be a full-size commercial plant, although units up to 318 Mg/d (350 TPD) may be designed.

PROCESS - Solid wastes, following rough shredding and ferrous metals removal, are loaded into the top of a vertical shaft converter. As the wastes descend through the converter, they are first dried by the rising hot gases and then heated to 315-982°C (600-1800°F). Undergoing pyrolysis, the wastes are thermally decomposed in an oxygen-deficient atmosphere, generating fuel gas and char. The fuel gas rises, and the char drops into the combustion zone, where it is burned with oxygen. The heat of combustion is sufficient to melt all inorganic materials such as glass and metal into a slag, which is tapped from the converter and quenched. The gas is cleaned in a water spray column and an electrostatic precipitator. Excess moisture is removed in a condenser.

The spent liquor removed from the gas in the spray column is processed in a decanting system where the oil and solid particulates are removed and the water recycled. Excess water is fed to a wastewater system for treatment and disposal to a municipal sewer.

The fuel gas has an average heating value of 14.2 MJ/m^3 (370 Btu/scf). Approximately 70% of the original energy content of the solid waste is recovered in the fuel gas, but roughly 1/3 of this energy, in the form of electric power, is required to operate the oxygen plant. The fuel gas can be burned in a boiler or chemically converted to methane, methanol, or ammonia.

ECONOMICS - For a proposed 5-converter, 1361 Mg/d (1500 TPD) system, 1976 capital costs are estimated at $62,400,000 including the front-end shredding and magnetic metals recovery systems. Annual operating and amortization costs are estimated at $13,620,000. In one of several cases presented in Section 8, product gas costs are indicated to be $1.841/million Btu with a $10/ton drop charge.



NAME - Occidental Flash Pyrolysis Process

TYPE - Conversion of the finely ground organic fraction of MSW to a liquid fuel by a rapid pyrolytic reaction.

DEVELOPER - Occidental Research Corporation, La Verne, CA.

HISTORY - Occidental (then Garrett Research) began work in 1968 on improved methods for isolating various fractions from waste materials and converting the organics to fuels by a proprietary pyrolysis system. A 6 Mg/d (7 TPD) pilot plant was used to investigate process variables, which after initial study of a range of conditions, were then optimized to yield an oil for direct utilization in utility boilers. Construction of a demonstration plant at El Cajon, California, was begun in August, 1975, and first testing began early in 1977. The plant handles 181 Mg (200 tons) of raw refuse per day and the liquid fuel product amounts to 31.8 m^3 (200 barrels) daily.

PROCESS - MSW is shredded to less than 10 cm (4 in.) size and magnetic metals are removed. An air classifier then separates most of the organic fraction from the inorganic. The classifier underflow stream is used as a feed to a recovery system. A trommel screen isolates essentially brittle (glass) materials and non-ferrous metals. Oversize from the trommel is returned to the grinders. The brittle fraction, ground to 44 to 840 μm (325 to 20 mesh), is pulped in water in the presence of proprietary chemicals and from a series of froth flotation tanks is produced a material that is 99.5% glass and containing approximately 70% of the glass in the original waste. The aluminum-rich fraction is conveyed to the "RECYC-AL" unit, where linear induction motors separate away about 60% of the original non-ferrous metals by eddy current effects. The material contains 90 to 95% aluminum.

The light fraction is dried in a rotary kiln and amounts to 55 to 60% of the weight of the raw MSW. It is further ground so that 80% is less than 1200 μm (14 mesh) and then pyrolyzed at 500°C (950°F) to convert the organics to gaseous, liquid, and solid (char) products. Air is excluded from the reactor by using recycled gas for the carrier gas and heat exchange is accomplished by use of heated char being carried co-currently in the stream. Quench oil is used to terminate further decomposition of the product mix. A portion of the gas is used for fuel in the rotary dryer.

Some 20 percent of the dry feed becomes char having an HHV of 19.10 MJ/kg (8,200 Btu/lb), while 40 percent is converted to oil with an HHV of 24.6 MJ/kg (10,600 Btu/lb). The gas yield is 30 wt-% of the dry feed; it has an HHV of 15.0 MJ/Nm^3 (380 Btu/scf). On the basis of raw refuse, 38% is recovered as products, 44% is consumed by the process, and 18% is residue. Assuming the electrical power required for the plant to be generated by use of an equivalent amount of pyrolytic oil, an overall energy recovery of 33% results from this process.

ECONOMICS - Total capital cost for a 907 Mg/d (1000 TPD) plant is estimated to be $28.6 million or $10.13/Mg ($9.19/ton). Operating costs for this plant are estimated to be $19.07/Mg ($17.30/ton). Revenues would be $13.64/Mg ($12.37/ton) based on EPA standardized accounting format for a net cost of $15.56/Mg ($14.12/ton). At the 1814 Mg/d (2000 TPD) plant capacity level, this net is estimated to drop to $8.51/Mg ($7.72/ton).

COMBUSTION PROCESSES

Introduction

Incineration of combustible wastes reduces their volume and converts them chemically into products that usually can be safely discharged into the environment after processing through applicable pollution control equipment. Most combustible wastes, whether solid, liquid, or gas can be incinerated, although handling care must be taken with plastic, toxic, or hazardous waste.

For ideal incineration, combustible waste must be well mixed with air in the proper proportions, ignited, and retained in a hot area - the combustion chamber - until it is completely burned. When the waste materials are combustible gases, liquids, or pulverized solids, this is relatively easy to do. Some wastes, however, have significant percentages of moisture, noncombustibles, or are not pulverized, and these require special incinerator designs.

The principal products of any combustion are water vapor, oxides of carbon and sulfur, and nitrogen. Some of these oxides, for example sulfur dioxide (SO_2) are air pollutants. Municipal solid waste, fortunately, has a low sulfur content. Plastic wastes often contain chlorine, which can result in the formation of hydrochloric acid (HCl) during combustion. Toxic and other hazardous wastes usually can be safely incinerated by maintaining a high temperature and long residence time to insure that they break down completely into less harmful products. In several cases, however, the oxidized species are as toxic, or even more so, than the original compounds. Fluorinated hydrocarbons, for example, whether in the form of aerosol propellant or the non-stick polymer coating on kitchen utensils, can thermally decompose into compounds having a high order of inhalation toxicity and the fully oxidized form, hydrogen fluoride, is a gas with a Threshold Limit Value of 8 ppm for a 1-hour exposure.

Combustion of solid and liquid wastes, and occasionally also gaseous wastes, produces fly ash, which is an air pollutant if allowed to escape. The amount of fly ash depends on combustion efficiency and the percentage of noncombustible material in the incoming waste, including coatings on paper stock, minerals in wood and agricultural crop waste, and dust in blast furnace gas.

Combustion of waste materials releases significant quantities of heat, which is taken out of the combustion chamber in the combustion products, through the furnace walls, or transferred back into the incoming waste. Originally, when the intent of incineration was simply to consume a waste material, the heat that is produced became a waste. More recently, the need to have greater control over the combustion process, to reduce the stack gas temperature to permit the removal of any fly ash, and to avoid the use of more expensive conventional fuels, has brought about a reawakening of interest in usefully recovering heat from the combustion of municipal, industrial, and agricultural wastes.

Combustion of Municipal Waste

By 1920, more than 200 municipal incinerators were operating in the United States (B-106), and many of these were equipped with boilers for the production of steam. A large number failed to operate satisfactorily because of poor design, unskilled operation, and use of too little auxiliary fuel. Throughout this period, incinerators were built of refractory brick, with a waste heat boiler added when heat recovery was practiced. Fly ash control was always a problem, and when air pollution laws began to tighten, most incinerators were faced with either shutting down or adding expensive air pollution equipment.

Meanwhile, incineration with heat recovery was widely practiced in Europe, with the steam being used for district heating or electric generation. By removing the heat to make steam, the incinerator exhaust stack gases were cooled sufficiently to permit the use of high efficiency electrostatic precipitators to remove the fly ash. The walls of these furnaces were made of closely packed water tubes which formed the steam boiler, resulting in the term "waterwall" construction. From being an added-on part of the incinerator, the boiler had become an integral part of the furnace combustion chamber, just as in any modern fossil fuel steam generating plant.

Waterwall Furnaces

Refractory walled incinerators require a very large air supply, between 100% and 200% in excess of the air theoretically required for combustion (Ref B-107). Waterwall incinerators require only 25% to 30% excess air (Ref B-107), an important advantage, because this means that, for a given capacity, the incinerator and pollution control equipment will be smaller for waterwall construction.

Currently, there are three basic designs of waterwall incinerators: mass burning in a thick bed on a moving grate, semi-suspension firing with burnout on a traveling grate, and supplementary firing in an existing boiler.

The mass burning design follow configurations proven in European operation. A cross section of a typical facility is shown in Section 3 under the description of the RESCO, Saugus, plant. The boilers are especially adapted for burning low grade fuel with high ash content. Refuse placed in a hopper falls down a chute and onto the moving grate. The refuse in the chute forms a plug against flashback from the boiler, with the rate of feed being governed by the movement of the grate.

There are several types of moving grates, but they all work to agitate and tumble the wastes to promote complete and uniform combustion. The reciprocating grate slopes downward from the feed end. Every other grate bar moves, pushing the burning refuse down the grate and agitating it. As with most types of grates, there may be as many as three major sections with a step in between, over which the waste falls to improve mixing.

The reverse reciprocating grate has sliding grate bars that push upwards and backwards instead of along the path of refuse travel. This design provides deep beds with more tumbling motion, and is common in large plants.

The roller grate consists of a number of turning cylinders arranged in steps, so that the waste is repeatedly tumbled as it is burned.

The traveling grate consists of an endless conveyor that carries the burning waste through the combustion chamber. Although there may be several stages, the grate itself does not agitate the waste, so it is not as commonly used in mass burning furnaces as the other types.

In all mass burning designs, the combustion bed is very thick, as much as 1 m (3 ft) deep. The grate is adjusted to achieve complete burnout of the refuse before it drops into the ash discharger, which often includes a quenching system.

Another type of firing system involves fuel suspension or semi-suspension. Both require mechanical processing of the waste to concentrate the combustible fraction and to reduce the particle size of the waste. The shredded and classified waste is then introduced into the furnace by a mechanical or pneumatic feeder. The refuse ignites in suspension and because it is surrounded by air undergoes rapid combustion. In semi-suspension systems, the burning refuse falls on a traveling grate where it completes burning in a relatively thin bed. Supplementary firing of wastes in utility boilers can be accomplished in furnaces designed for burning pulverized coal, since they are equipped with ash grates. The pulverized, classified refuse is blown tangentially into the four corners of the furnace, creating a swirl pattern that promotes complete combustion in suspension. Because of its relatively heavy ash and slow burning characteristics, the refuse in most cases to date has amounted to only 10%-15% of the heating value of the total fuel.

The air for supporting combustion is typically preheated and blown into the furnace. In designs using moving grates with thick combustion beds, most of the air is underfire air blown up through the grates. Overfire air, blown in over the burning refuse, is carefully aimed and controlled to provide the desired flame pattern and residence time. In semi-suspension furnaces, most of the air is overfire air, but underfire air still is necessary to promote complete burnout on the grate. In supplementary firing systems, the airflow direction and quantity is calculated to keep the burning material in turbulent suspension, with none of the air being supplied through the grate.

The walls of these furnaces are made of panels consisting of vertical tubes, typically 6.3 cm (2.5 in.) in diameter on 7.6 cm (3 in.) centers with a bar welded between the tubes. These waterwalls usually extend down to the grate level, and have a covering of refractory for a short distance above the grate to protect the tubes and reflect heat back onto the grate. Most of the tube area is uncovered, because the refractory acts as an insulation, but areas subjected to wear may also have protective coatings.

The waterwall section is the boiler or steam generator that heats liquid water into steam. It is followed by a section of tubes hung in the hot gas flow called the superheat section. The steam coming from the boiler contains no liquid water droplets, but it would if its temperature dropped only a few degrees. In addition, there is still significant heat remaining in the flue gases that could be recovered in the steam. Therefore, in the superheat section the steam temperature is raised well above the saturation (vapor) point, enhancing its ability to do useful work.

Following the superheater is the economizer section, another section of tubes hanging in the still hot flue gas stream, in which the boiler feed water is heated to a point just below boiling.

Because of the high fly ash and soot content of incinerator flue gases, the passages between the tubes of the pendant superheater and economizer can easily become blocked. Some form of soot blowers or mechanical tube rappers must be provided to knock the accumulation off the tubes. In addition, the tubes are more widely spaced than is usual on oil or natural gas fired boilers in order to reduce the chances of bridging between them.

From the incinerator, the cooled combustion gases go through pollution control devices to remove any remaining fly ash, through an induced draft fan, and out the stack. Wet scrubbers and filters were originally used to collect the fly ash, but a need for greater efficiency in removing particulates caused electrostatic precipitators to be used almost exclusively for a number of years. These devices, in which static electricity captures the particles with an efficiency of over 99%, are still the principal means of pollution control used, but new filter systems developed are equally effective and are beginning to be utilized.

In addition to erosion and fouling by fly ash, chemical corrosion can be a problem when certain types of wastes are used as fuels. Corrosion comes from at least three sources: oxygen-deficient burning resulting in a reducing atmosphere; presence of chlorine, certain metals, and other chemicals; and presence of moisture (Ref. B-107, B-108). Oxygen deficient burning can occur, despite the provision of excess under-and over-fire air, when uneven distribution of fuel or air results in partly oxidized (burned) gaseous products such as carbon monoxide. In seeking more oxygen to complete combustion, these gases reduce the oxygen in the protective layer of metallic oxides on the boiler tubes, paving the way for other corrosive activity. The cyclic reduction-oxidation reactions can result in a high degree of tube wastage. Chlorine from plastics and rubber, and tin and zinc from food containers, react directly with the iron in the boiler pipes. All forms of corrosion are greatly enhanced by the presence of moisture, which can occur if the boiler is allowed to cool, for example, by shutting down on weekends and holidays. The widely varying results reported on corrosion in refuse fired systems is undoubtedly a result of the heterogeneity of the waste and widely varying operating practices of different systems.

Other Municipal Waste Combustion-Energy Recovery Systems

There are other municipal waste combustion systems with energy recovery, including starved-air incinerators, vortex furnaces, and fluid bed combusters. They are aimed at overcoming the major disadvantage of a waterwall furnace: its great size, and consequent high cost.

Starved-air incinerators are made by a number of firms in varying capacities up to about 13 Mg (14 tons) per day (Refs. B-109, B-110, B-111, B-112), but can be installed in multiple units to achieve the desired plant capacity. Municipal waste is burned as received in a primary combustion chamber with insufficient oxygen for complete combustion. The combustible materials that are not burned are gasified. This gas is then burned in a secondary combustion chamber with excess air, achieving temperatures sufficiently high to burn out the carbonaceous fly ash. For a unit with a capacity of 1.3 Mg (2,800 lb) per hour, the primary combustion chamber measures approximately 4 m (13 ft) long by 3 m (10 ft) in diameter; the secondary chamber is much smaller. Overall dimensions are about 9.4 m (31 ft) long, 4 m (13 ft) wide, and 8.5 m (28 ft) high, including the stack.

These incinerators are designed with a minimum of ancillary equipment, and most do not have automatic ash handling equipment. They therefore operate on a 24 hour cycle. In the morning, after being cleaned out from the previous day, they are preheated with auxiliary fuel, either oil or natural gas. Waste is fed in by an automatic loading system, consisting of a hopper, a hydraulic ram, and fire door. Charging normally continues for seven to eight hours and burndown for another three hours, with auxiliary fuel being used throughout this period. The unit is then allowed to cool overnight, and is cleaned of ash in the morning before a new cycle begins. In contrast to large water wall furnaces, there are few increased maintenance problems due to this cool down, due to the refractory lining of the small unit and the absence of bare metal air pollution control equipment.

Because of the two stage burning with limited air in the primary stage, gas velocities are kept low, avoiding fly ash pickup. The combustion in the second stage is in the gas phase, permitting a hotter and more complete oxidation. The result is very low stack emissions, averaging 0.07 to 0.19 g/Nm^3 (0.03 to 0.08 grains/SCF) (Ref. B-111). This is below the U.S. Environmental Protection Agency's limit of 0.19 g/Nm^3 (0.08 grains/SCF) for large incinerators.

Where energy recovery is practiced, a waste heat boiler of either the water tube or the fire tube type is installed in the flue, although an air or water heater could also be used (Ref. B-109). Energy recovery can be regulated by controlling the amount of hot flue gas that is passed through the boiler, either with mechanical flap valves or aerodynamic valves. The steam produced is not sufficient for efficient electrical generation, but can provide process steam for many industrial applications. In a recent test, one unit produced 21.5 Mg (47,425 lb) of steam at 791 kPa (100 psig) from 7.5 Mg (8.3 tons) of refuse and 102.2 m^3 (3610 ft^3) of natural gas auxiliary fuel. Weight reduction of raw waste in these incinerators averages 68%, and volume reduction 93%, comparing very favorably with large waterwall incinerators.

A vortex furnace is a circular horizontal or vertical furnace in which air is blown in tangentially, creating a swirling vortex. Wastes can be either finely ground and blown in to burn in suspension, or can be mass burned, with the hot gases scrubbing over the waste. In either case the object of the turbulent vortex is to provide good mixing between combustibles and the air to promote complete and rapid burnout. In order to achieve maximum residence time, the aerodynamics of the vortex is often arranged so that the air must follow a spiral along the walls of the furnace and mix with rising volatile matter. Only after the air and volatiles are burned to low density combustion products can they escape through the center of the vortex.

In a vertical cylinder, refuse is fed from the bottom and air is introduced high up through side ports. The air moves in a downward spiral along the walls to scrub the fuel bed and mix with rising volatile matter.

In the horizontal cylinder, refuse is fed by a hydraulic ram. The combustion air is delivered to the combustion chamber via a manifold and distributed in such a manner as to set up a circular turbulent action. In both designs, the walls of the furnace are cooled by the incoming air.

During the period of 1967-70, a pilot vortex incinerator plant was built and tested at the EPA's Solid and Hazardous Waste Research Laboratory, Cincinnati, Ohio (Ref. B-113). The purpose of the project was to advance the state-of-the-art by improving combustion efficiency, volume reduction, and mechanical reliability and to reduce air pollution to an acceptable level.

The completed incinerator was a horizontal cylinder 3.66 m (12 ft) long and 1.83 m (6 ft) in diameter. Refuse was charged to the incinerator by a hydraulic ram. The stoking action was accomplished by the incoming refuse pushing the burning refuse across the floor of the incinerator and finally out the other side into the residue pit. This kind of stoking eliminates the need for grates. Any slag that was formed flowed or was pushed into the residue pit. Heated combustion air was injected so as to set up a cyclone or vortex action aiding the stoking action by exposing more burning surface to combustion. The desired burning rate was 454 kg/h (1000 lb/hr), with 90% volume reduction and 80% weight reduction. The cyclonic movement of the gases down the combustion chamber was to provide at least 0.5 second residence time at temperatures in excess of 1315°C (2400°F).

The data collected on the incinerator's combustion chamber operations indicated it did a very effective job in burning untreated municipal refuse. Low solid particulate concentration, small particle size, high heat release rates, and high carbon dioxide concentrations indicated the combustion chamber performed well. The burning rate was higher than the design specifications, but was necessary to sustain high combustion temperatures. The result of the elevated burning rate was a poorer quality residue, even though the volume and weight reductions were acceptable. Adverse conditions in the stack led to termination of the project. Stack gas tests indicated that the concentration of total particulate matter was in excess of established regulations. This was attributed to a high concentration of water soluble matter in the effluent that counted as particulates by the test method and the use of an inefficient cyclone as a control device.

Another vortex incinerator development project was conducted at Shelbyville, Indiana, by General Electric and the City of Shelbyville with EPA support (Ref. B-114). Municipal refuse was used as fuel. Finely shredded combustibles were blown tangentially and at high velocity with primary air into a horizontal cylindrical furnace to form a vortex. The facility was built with a refuse receiving apron, primary shredder, rotary air classifier, secondary shredder, and cylindrical furnace. Pollution control depended only on a single cyclone for large particulate removal.

Some 109 Mg (120 tons) per day of raw refuse was accepted, with 23 Mg (25 tons) per day of heavy materials, such as metals, glass, plastics, rock, etc. separated. Thus, 86 Mg (95 tons) per day of combustible refuse was incinerated in the 2.59 m (8-1/2 ft) diameter by 3.96 m (13 ft) long vortex furnace.

The secondary shredder reduced combustibles to less than 12 mm (1/2 inch) in size and a pneumatic feeder blew the material into the vortex incinerator. Secondary air was blown in tangentially along the length of the incinerator cylinder through inlet ducts. The temperatures reached during combustion were 982 to 1093°C (1800 to 2000°F). All ash was carried out with the exhaust gases at high velocity. However, certain heavy items and non-combustibles that passed through the front-end separator systems were caught in the incinerator and it was necessary to open the furnace at least once each day to remove such material.

A private venture in designing and operating a vortex furnace is being made by ACES in Red Lion, Pennsylvania (Ref. B-115). The system has a front end consisting of shredding, air classification, and magnetic separation. The prepared refuse is fed into the top of a vertical, refractory line circular furnace along with the primary air. As it falls through the furnace, it is swirled into a vortex by the tangentially blown secondary air. Combustion of the waste, which averages 34% moisture, takes place in less than two seconds, at temperatures as high as 1343°C (2450°F). The combination of a turbulent vortex and a low 20% to 25% excess air results in efficient heat exchange. Approximately 11% of the input fuel is inerts, largely glass. Ninety four percent of that comes out the bottom of the furnace as slag; the remaining 6% (less than 1% of the original input fuel) is carried over into the boiler.

For the original tests at Red Lion, the hot gases from the vortex furnace were taken through a refractory lined tunnel to a standard package firetube boiler rated at 11 340 kg (25,000 lb) of steam per hour at saturated conditions and 929 kPa (120 psig). During most of the tests the boiler was operated in the 8164 to 9072 kg (18,000 to 20,000 lb) per hour range, exhausting the gases to the stack at 177°C (350°F). Particulates downstream of a wet scrubber measured 0.60 g/Nm^3 (0.25 grains/SCF) with 6 ppm of hydrocarbons and no CO.

On a gross heat input basis, the developer claims an efficiency of 64%. The moisture in the refuse accounted for 7.8% of the lost 36%, 12% was in the exhaust, and 8% was contained in the hot slag.

Fluid bed furnaces take a different approach to holding wastes in suspension while they are burned. An inert material, such as sand, is "fluidized" by blowing air up through it. Through use of the right amount and velocity of air, the bed can be made to behave very much like a liquid, and refuse fed into the fluid bed will be brought into close contact with the hot sand. Very high rates of heat transfer can be obtained because of the contact with the sand, and the fluidizing air provides all of the oxygen required for combustion.

The CPU-400 pilot plant, built and operated by Combustion Power Co. Inc. in Menlo Park, California, employs the fluidized-bed combustion process. Shredded and air classified combustibles are burned at high pressure in a combustor, with the combustion gases then used to drive a turbo-electric generator (Ref. B-24). The combustor is a 6.7 m (22 ft) high by 2.9 m (9-1/2 ft) diameter cylindrical carbon-steel pressure vessel with dished heads and lined with fire brick. The cylinder is penetrated by 161 air diffusers. An oil burner used for preheating the sand bed during cold system startup is mounted in the top dome of the combustor. Six oil guns penetrate the combustor immediately above the distributor plate for use during start up.

The fluid bed combustor provides excellent combustion at temperatures of 816 to 982°C (1500 to 1800°F), resulting in low emission of contaminants. A train of three separators removes sand and ash particles from the exhaust gas prior to its entering the turbine. A serious difficulty, not yet eliminated, is carryover of various fine particles that erode the turbine blades. A moving bed granular filter has recently been studied in this EPA-supported work, but the equipment experienced a structural failure early in the test program. ERDA has now accepted the responsibility for further development of this device.

Both the vortex and fluidized bed furnaces work best when mechanical pretreatment of refuse is used to remove heavy materials and non-combustibles that have bad effects on their operation. Raw refuse before being fed to the furnace is usually shredded, the ferrous metals removed, and the heavy fraction isolated by means of an air classifier.

Both systems have also been used with add-on boilers, called waste heat boilers because their original use was to capture heat from gases in incinerators and other heat generating processes that would otherwise be wasted. These boilers have upper and lower drums connected by water tubes, and are made as package units by a number of manufacturers.

Combustion of Industrial and Agricultural Waste

In the constant effort to reduce costs in industrial production, there is naturally a continuing effort to find ways to recycle or use the process wastes. Saw mills may have been among the first to use their wastes to produce energy for running the process, but today many industries practice energy conversion and recovery. In recent years, interest in waste-to-energy conversion has increased. This is because of cost increases for competing fuels, restrictions on more conventional disposal methods such as landfills, the need for heat removal to make clean up of incinerator flue gas easier, and the low sulfur content of most process wastes.

In general, solid wastes can be burned on a fuel bed or in suspension. Liquids are usually introduced into combustion zones as a fine spray. Gases can be burned as they are produced, although some, like blast furnace gas, require cleaning to remove particulates. A variety of furnace types can be used to consume these wastes, including waterwall furnaces, refractory furnaces with package boilers, vortex and cyclonic furnaces, fluid bed combustors, and molten salt baths.

Waterwall furnaces for industrial wastes are very much like those for coal or municipal waste; firing can be either on a grate or in suspension, depending on the waste characteristics. Feed mechanisms for relatively wet materials such as sugar cane bagasse act like a rotating series of paddles that toss the chopped bagasse onto a traveling grate. At the other end of the spectrum, a large carbon monoxide boiler used with an oil refinery needs only huge ducts and gas ports to carry the hot gas from the catalytic cracker into the furnace. Wood waste boilers are very common at saw mills; a listing by just one stoker manufacturer indicates seventy-six installations burning bark and other wood wastes with their equipment; it is estimated that there are in excess of 500 such systems in the U.S. A large unit installed by the Weyerhaeuser Company at Longview, WA, produces 249 480 kg (550,000 lb) of steam per hour on hogged fuel using suspension firing with a burnout grate fed by a vibrating flow splitter. The steam is run through a turbogenerator to produce electric power and then goes to operate plant processes such as mill dryers and digesters.

Refractory furnaces were in use before the waterwall type, and are still used in some applications. Coffee grounds, which have a high moisture content, are sometimes burned in a cell-type furnace, either on flat grates or on the furnace floor. Liquids can be sprayed into a refractory furnace by an atomizing burner, and small carbon monoxide boilers use refractory furnaces in conjunction with a package boiler. These systems are usually low waste volume installations that cannot justify the design of a special furnace and boiler; it is much quicker and easier to use shop-built package units.

Vortex and cyclonic burners hold fuel particles in the burner by centrifugal force until they are completely burned up. Air is blown tangentially into the furnace; fuel is either fed in with the air (vortex type) or fed in onto a rotating hearth (cyclonic type). Because these furnaces operate with a low excess-air ratio with essentially all of the heat release from the fuel taking place inside the relatively small combustion chamber, combustion gases can be ducted to a package waste heat boiler or to some other use of hot dry gases, such as a lumber kiln or veneer dryer. The Goodyear Tire and Rubber Company has reported success in dealing with a hard-to-dispose-of waste, used tires. A rotating hearth furnace is used to destruct the tires; the hot combustion gases are taken through a conventional two-drum design waste heat boiler with bare tubes in the first section and finned tubes in the second section. A scrubber is used to clean up the cooled flue gas before it is discharged (Ref. B-116).

Fluid bed combustors, similar to those used for municipal waste and sewage sludge, are widely used in industry for drying, converting, and burning a variety of materials. They are widely used in the pulp and paper industry to convert wastes into energy, and their use is increasing as supplies of natural gas decline. Fluidized beds can be made with in-bed heat exchangers, waterwalls, or package boilers. They have the advantage for many installations that combustion can be obtained at temperatures that can be controlled to within 5.5°C (10°F). Carryover of particulates is minimized, although a scrubber may be required depending on the characteristics of the waste.

Another heat recovery combustion system frequently used in the pulp and paper industry is wet air oxidation. There are numerous examples of wet wastes that have potential for heat recovery, except that all of the recovered heat would be required to dry the waste to the point where it could be burned. To avoid this problem, these wastes can be combined with slightly excess air in a reactor under elevated temperatures and pressures. Wet air oxidation is very much a temperature-dependent reaction in that different organic compounds react at different temperatures. Virtually complete oxidation will take place at temperatures above 316°C (600°F). At these temperatures, pressures of approximately 20.7 MPa (3000 psi) are required to keep the necessary amount of water in the waste liquid (Ref. B-117). Wet air oxidation temperatures cannot exceed the critical point of water, 374.1°C (705.4°F). Production of steam at temperatures of more than 287.8°C (550°F) is therefore not practical, as there must be sufficient temperature differential to give good heat transfer. However, abundant energy in the form of hot water or low pressure steam can be made. It can be used in areas such as pre-heating boiler feed water, area heating, process heat, and drying.

A number of other incineration processes have the potential for energy recovery, although application is not necessarily yet being made. Molten salt baths, for example, can be used to destroy many toxic wastes because the salt bath can chemically alter the wastes besides oxidizing them. Pesticides, low-level radioactive wastes, and explosives are among the other wastes that can safely be destroyed by this system (Ref. B-118). Maximum temperature for this process is limited to 980°C (1800°F) to avoid overactivation of the salt. There is some salt carryover from the molten bath, but the process developers felt that the problems of designing a boiler to operate under these conditions were well known and would present no difficulty to heat recovery. No commercial energy recovery system has yet been built.

Descriptions of Key Projects

Brief descriptions of typical combustion projects are presented on the following pages.

NAME - RESCO Refuse Burning Steam Generator, Saugus, Massachusetts

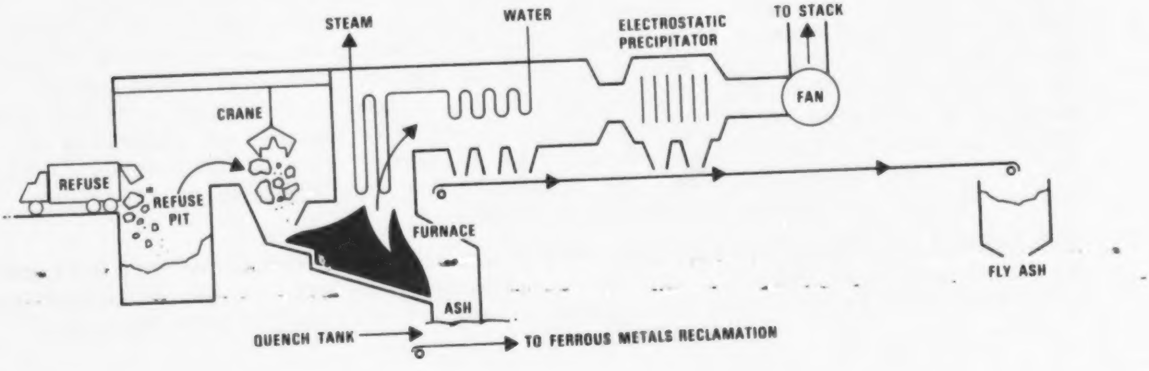
TYPE - Mass burning waterwalled combustion system

DEVELOPER - Refuse Energy Systems Company

HISTORY - Feasibility studies were made in 1969 and construction began in June 1973; initial testing began in late 1975 and the facility is now fully operational.

PROCESS - Designed by Wheelabrator-Frye, Inc. and built by M. DeMatteo Construction Co., this 1090 Mg/d (1200 TPD) facility is based on proven technology developed by the Swiss firm of von Roll. MSW from surrounding communities is received and stored in a pit capable of holding refuse for more than 5 days operation; only bulky wastes are fragmented. Furnace feed hoppers are supplied by overhead cranes. Two waterwall furnaces (max. capacity = 680 Mg/d each) with 3-section reciprocating grates operate at 900°C (1650°F) to produce 3810 Mg/d (8.4 million lb/day) of steam at 4.86 MPa (690 psig) and 468°C (875°F). It is piped to the nearby G.E. Lynn Works. Two Lurgi electrostatic precipitators reduce particulate emissions to below 0.05 grains/SCF and the clean flue gas is discharged through a stack 54 m (178 ft) tall. Standby oil-fired boilers are present to assure a product steam supply.

ECONOMICS - Capital costs were $38,268,000 for the total system. Original drop charges to the participating communities were $14.33/Mg ($13.00/ton), with RESCO being permitted to charge more for later cities; a cost escalation formula is incorporated into contracts. Being a private venture operation, details of revenues and operating costs are not available.



NAME - Hamilton Solid Waste Reduction Unit (SWARU)

TYPE - Semi-suspension fired steam generator burning processed waste

DEVELOPER - Regional Municipality of Hamilton Wentworth, Ontario, Canada

HISTORY - Design was initiated in 1968, with initial start-up in February, 1972, and commercial operation in June, 1972.

PROCESS - Hamilton is unique in burning prepared refuse partly in suspension, with burnout on a traveling grate. This technology was taken from the wood products industries. Incoming refuse is dumped into a pit with a conveyor bottom, picked over manually to remove large materials, and carried to four vertical-shaft pulverizers. These are relatively light duty, 150 kW (200 HP) units, selected on the basis of a study that indicated it would be more economical to landfill large objects, or those difficult to shred, than to provide larger shredders. Ferrous metals are recovered magnetically and the remaining refuse is either sent directly to the furnaces or stored for later use in a 21.3 m (70-ft) diameter Atlas bin. Figure 2 shows a schematic of the facility.

The plant has two Babcock and Wilcox waterwalled furnaces, each capable of burning 272 Mg (300 tons) per day. The prepared refuse is introduced by a swinging distribution spout and three parallel pneumatic injection chutes. The light combustibles burn in suspension, with the non-combustibles and heavy burning objects burning out in a thin bed on the traveling grate. The ash is landfilled.

SWARU is capable of generating 47 944 kg (105,700 lb) of steam per hour in each boiler, at a pressure of 1.82 MPa (250 psig) and saturated conditions. Some 50% to 60% of the steam is used in turbines for running plant equipment. The remainder is condensed in roof-top air-cooled condensers and recirculated. The gases leave the boiler at 310°C (590°F) and cleanup is performed by two Lurgi design electrostatic precipitators in series per boiler.

The major problems in the plant have been in the materials handling system, where bridging, plugging and spilling of the refuse required design changes.

ECONOMICS - SWARU cost a total of $9 million when it went into operation. It has been estimated that minimum plant improvements to correct operating problems would cost an additional $1 million. The 1975 operating and maintenance costs totalled $2,117,000 for disposing of 43.5 Gg (48,000 tons) of solid waste. This is a disposal cost of $48.62/Mg ($44.10/ton), a very high figure. If the plant were to be operated at 85% of capacity, it would be capable of disposing of 168.9 Gg (186,150 tons) of solid waste at an annual cost of $2,649,065 (1975). This would significantly lower the disposal cost to $15.69/Mg ($14.23/ton) before taking any credit for possible revenues.

The plant recovers ferrous metals, which are sold, and steam for which there is no local market at present. If the steam were to be sold, a distribution system would have to be built, estimated to cost $4 million in 1976 dollars.

NAME - Nashville Thermal Transfer Corporation, Nashville, Tennessee

TYPE - Mass burning, waterwalled boilers with reciprocating grates, producing steam for district heating and cooling.

DEVELOPER - Nashville Thermal Transfer Corporation, 110 First Avenue South, Nashville, Tennessee, a non-profit Tennessee corporation.

HISTORY - As part of an urban renewal program for downtown Nashville, THERMAL was created to be the developer and operator of a district heating and cooling system. In 1970, a study was made that established the feasibility of generating the required steam by burning refuse. Design was started in early 1971 and construction in June, 1972. Steam service, using an oil fired boiler, was initiated in February, 1974, and incineration of MSW began in May, 1974. A number of operating problems, including water tube and control system failures, had to be overcome. The most widely publicized problem has been THERMAL's non-compliance with air quality standards due to reliance on a wet scrubbing system for flue gas clean-up. One electrostatic precipitator is successfully operating and a second is now being installed.

From the refuse pit (see Figure 4), unprocessed solid waste is charged by an overhead crane to the feed chute of the two furnaces and onto a four section Detroit Reciprocating Grate Stoker; 653 Mg/d (720 TPD) can be burned. The hot combustion gases generate steam in a pair of Babcock and Wilcox boilers. Many of the auxiliaries have steam turbine drives, which do not have the high torque and rapid response characteristics that would be desirable. Similarly, the pneumatic and electric control systems were not originally designed with sufficient independency and redundancy, and some problems have been experienced with them. Steam is produced at 2.86 MPa (400 psig) and 325°C (620°F). For the district heating system this is reduced to 1.14 MPa (150 psig) in the auxiliary drive turbines. Chilled water is supplied at 1.34 MPa (180 psig) and 5°C (41°F).

Originally, the flue gases were passed through multi-cyclone dust collectors and then through wet scrubbers. The scrubbers were specified to remove 95% of all particulate matter based upon a 5 μm mean particle diameter. However, an average of 28% of the particulates in the flue gas are under 5 μm, and 21.4% are under 1 μm. These small particles are difficult to remove with scrubbers and the new electrostatic precipitators had to be purchased.

ECONOMICS - The initial cost of the facility was $16,500,000, but the start-up problems have necessitated a capital completion program estimated to cost an additional $8,000,000. The start-up problems caused shortfalls in revenues and overruns in expenses. Upon fulfillment of the capital completion program and receiving an increase in the annual service payment from Metropolitan Nashville, it is anticipated that THERMAL's operating revenues will be adequate to meet operating expenses.

NAME - CPU-400

TYPE - Refuse-fired high pressure fluid bed incinerator coupled to an open cycle turbo-electric generator system.

DEVELOPER - Combustion Power Company, Menlo Park, California, under contract to the EPA's Office of Research and Development.

HISTORY - The initial proposal for the CPU-400 concept was submitted to the U.S. Department of HEW in September, 1966. A preliminary design study was made between June, 1967, and June, 1968. From mid-1968 to late 1970, subscale experiments to evaluate basic equipment items were conducted under contracts with HEW, and later, EPA. Pilot plant design and construction were performed between mid-1970 and April, 1973. Further contracts have been made between Combustion Power and EPA for test and development since 1973. In addition, tests have been made using high sulfur coal for the Office of Coal Research and ERDA and using wood waste for a major forest products company.

PROCESS - The CPU-400 system has four major sections: solid waste processing, combustion, gas cleanup, and power generation. Pilot plant testing has been at the 90 Mg/d (100 TPD) level. The solid waste processing facility includes a tipping/storage area, two shredders, an air classifier, and materials recovery systems. The light fraction from the air classifier is taken to a refractory-lined fluid bed combustor 2.2 m (7.1 ft) in diameter and 4.3 m (14 ft) high. Two rotary airlock feeders are used to introduce the fuel to the bottom of the combustor's 61 cm (2 ft) deep bed of sand at a rate of 45.4 kg/min. (100 lb/min.). Air from the turbine compressor at about 400 kPa (58 psia) is used to fluidize the sand and provide combustion air. The combustion gases are taken through a gas cleanup system to remove particulates before being passed through the turbine. A 1000 kW axial flow gas turbine is used to extract energy from the hot gas stream to drive the air compressor and the electric generator.

The most severe problem in the system has been the failure to achieve adequate gas cleanup. Carryover of aluminum oxide particles from solid waste formed deposits on the first stage turbine stator blades. Subsequent sloughing of the aluminum oxide deposits resulted in severe downstream turbine blade erosion. The initial gas cleanup system used three stages of cyclones, but the second and third stages became plugged and allowed uncleaned gas to pass into the turbine. The second stage has been enlarged and a granular filter developed as the third stage. Tests of this system indicate that more development work is necessary.

ECONOMICS - An estimate of costs and revenues for a 12 MW, 544 Mg (600 tons) per day facility published in September, 1974, set the installed capital cost at $10.8 million. Total annual cost was estimated to be $2,500,000 and revenues from the sale of electricity only to be $1,140,000, leaving a net annual cost of $1,360,000 or $7.61/Mg ($6.90/ton) of refuse disposed. Revised economics should be made when the design is finalized and verified.

NAME - Longview, Washington, Plant Power Boiler

TYPE - Wood waste semi-suspension fired steam generator

DEVELOPER - The Weyerhaeuser Company, Longview, Washington

HISTORY - In operation since January, 1976.

PROCESS - Hogged fuel, bark, and other manufacturing wood waste averaging 0.64 cm (1/4 in.) in size, but with pieces up to 10 cm (4 in.), is pre-dried in a rotary dryer, using wood fines as a fuel. The moisture content of the wood waste fuel is reduced to approximately 30% to 35%. The drying has been found to be necessary because the fuel is kept in an outside stockpile, an enclosed storage system not being considered justified. From the dryer, the waste wood fuel is fed to the furnace by a vibrating flow splitter. A large part of the fuel is burned in suspension, with final burnout taking place on a grate in a manner similar to the MSW waterwall incinerator at Hamilton, Ontario. The boiler produces 250 000 kg/h (550,000 lb/hr) of steam at 8.6 MPa (1250 psi) and 510°C (950°F). The steam is expanded through turboelectric generators before being used to heat mill dryers, digesters, and other plant processes.

According to Weyerhaeuser engineers, electrostatic precipitators cannot be used on wood-fired furnaces because of resistivity characteristics of the fly ash, so two-stage mechanical collectors are used for flue gas cleanup.

ECONOMICS - No data have been released on the capital or operating costs, but they could be considered to be equivalent to other large waste-fueled waterwall steam generators.

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APPENDIX C

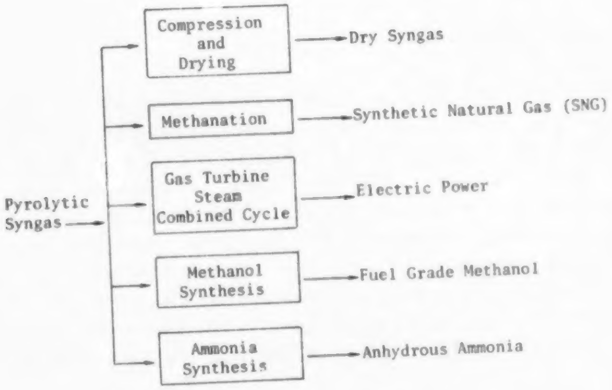
ALTERNATIVE USES OF PYROLYTICALLY-FORMED SYNGAS

INTRODUCTION

Conversion of solid waste to a syngas has been treated in Section 8. The base case analyzed was a front end and gasifier to process nominally 1361 Mg/d (1500 TPD) of raw refuse in the Union Carbide Corporation (UCC) Purox system. Steel and aluminum were recovered, the syngas dried and compressed, and then delivered to a power utility or industrial customer by short pipeline. Construction and operating costs were developed along with an economic analysis to show the unit cost of the syngas as a fuel.

In that the discussion within the main body of the text was to be limited to a specific conversion system, the analysis was taken only through the step of conditioning the Purox gas. Because this gas has a substantial component of carbon monoxide and hydrogen with a negligible quantity of nitrogen, it possesses value as a feedstock for further conversion to other fuels or chemicals, in addition to being able to be used directly to produce industrial heat or electric power. It serves, therefore, as an excellent model for the analysis of possible costs for these alternative uses. Rather than developing an entirely separate case with new assumptions on composition and initial costs, it is convenient to directly utilize the information presented in Section 8 as a starting point. The discussion presented within this Appendix is entirely the responsibility of Parsons and in no way is it implied that the Union Carbide Corporation necessarily concurs with the analysis or that UCC proposes to supply total systems described here.

The several alternative processes are shown schematically as follows:


Compression and Drying
Dry Syngas
Methanation
Synthetic Natural Gas (SNG)
Pyrolytic Syngas
Gas Turbine Steam Combined Cycle
Electric Power
Methanol Synthesis
Fuel Grade Methanol
Ammonia Synthesis
Anhydrous Ammonia

Ammonia is not produced as a fuel but almost all of it is made from fossil fuel, primarily natural gas. Its character as an energy form is by direct relation.

The Purox gas contains about 10% by volume of hydrocarbons. If the gas is to be converted to methane, methanol, or ammonia, provisions must be made to process the hydrocarbons by converting them to an appropriate mixture of CO and H_2 (pure H_2 for ammonia). Furthermore, the gas has trace contaminants that can affect catalysts and therefore needs careful experimental evaluation, which should include a pilot plant test of the gas treating and catalytic conversion units.

Practically all methanol or ammonia plants that have been constructed use natural gas and to a smaller extent naphtha as a feedstock. Industrial partial-oxidation units are now used to convert oil or coal to a syngas (Koppers-Totsek, Texaco, Shell). The high temperatures of 1539 to 1649°C (2800 to 3000°F) result in a gas with little or no hydrocarbon content. In the Purox reactor, the solid waste reduction to gas and char by pyrolysis takes place at temperatures of 538 to 760°C (1000 to 1400°F) and upwards of 10% to 11% by volume of hydrocarbons are formed. These can be reformed, otherwise they are used as fuel and their value as a source of H_2 and CO is lost. The Lurgi process for coal produces a similar gas, but to this date no ammonia synthesis plant has been constructed with the Lurgi gas because of problems in gas conditioning. Producing methane or methanol will be less difficult than producing ammonia.

Gas treating expertise and experience will be required in using pyrolytic gas for chemical synthesis processes. In particular a pilot gas treatment and conditioning unit with representative catalysts must be tested at the Purox demonstration site, otherwise the risks are high in building an expensive commercial chemical synthesis unit.

The information here should only be used as a guide for determining whether alternative end products are of greater value than the syngas or even in comparison with different solid waste disposal and processing systems. Such work has been accomplished specifically in two engineering and economic feasibility studies in the San Francisco and Denver areas by Parsons (Ref. C-1, C-2).

METHANE CONVERSION PROCESS DESCRIPTION

The syngas produced by the Purox process must be upgraded to meet current pipeline gas specifications. Eighty-eight percent by volume of the syngas is composed of a mixture of CO, CO_2, and H_2, plus 11% hydrocarbons, with an HHV of 14.57 MJ/Nm^3 (370 Btu/SCF). Pipeline gas, which is almost all methane, has an HHV 2.7 times higher. Methanation has been in existence for some time to reduce small amounts of CO in a hydrogen rich gas. Conversion of a syngas to pipeline quality gas by bulk methanation has not been applied commercially. However, presently occurring changes in the economics of the natural gas industry has generated great interest in syngas methanation. An applicable new process, known as the RMProcess, is discussed below.

A pilot methanation plant has been tested by The Ralph M. Parsons Company using gas from a Texaco partial oxidation unit in Montebello, California; oil resids or coal are used as feedstock. This process is a new approach to catalytic conversion of synthesis gas to methane. Appreciably reduced capital and operating costs for large-scale operations are projected as compared to existing schemes because a large recycle gas stream for temperature control purposes is not used and water-gas shift occurs in the same catalytic bed.

Flow diagram of the process is presented in Figure C-1. Table C-1 shows information regarding some of the several streams in the methanator system. The feed gas is stream 9 from Figure 35. The syngas is received at approximately 310 kPa (45 psia) and is compressed to 931 kPa (135 psi).

Condensed water and hydrocarbons are separated from the cooled gas, which is then passed to an absorption unit to remove acid gases. Hydrocarbons collected are used as fuel. The concentrate from the absorber unit is sent to a Stretford process unit where free sulfur is recovered, while releasing the CO_2 to the atmosphere. Sulfur is kept to less than 5 ppm in the feed gas to the methanator reactors.

The cleaned syngas, together with steam, then passes through the bulk methanator (Ref. C-3), which consists of a series of fixed-bed, adiabatic, catalytic reactors, as shown schematically in Figure C-2. Both the water-gas shift and methanation reactions take place simultaneously in the catalyst beds. Also, remaining light hydrocarbons with molecular weights greater than CH_4 are steam reformed and converted to methane in the same beds. Some reactions that take place are:

$$CO + H_2O \rightarrow H_2 + CO_2 \quad \text{(shift reaction)}$$

$$C_2H_6 + 2H_2O \rightarrow 2CO + 5H_2 \quad \text{(reforming)}$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O \quad \text{(methanation)}$$

Because the methanating reactions are exothermic, the gas temperatures reach 538 to 649°C (1000 to 1200°F). The presence of excess steam in the catalyst bed prevents carbon deposition on the catalyst at these high temperatures. Heat is removed by generation of high pressure steam in conventional heat exchange equipment. This stream is used in turbines to drive compressors. The residual low-pressure exhaust steam at both 827 and 414 kPa (120 and 60 psia) is returned to the process to provide water-vapor for the water gas shift conversion phase of the reaction and for reboiler use in absorption liquid regeneration. After having passed through the bulk methanators, a second absorber unit removes CO_2 formed in the methanator train, and the gas stream passes through a final stage of dry methanation. After dehydration, it emerges as pipeline-quality gas ready for injection into a utility pipeline. Pressures do not exceed 1207 kPa (175 psia) in the process.

The process is capable of performing satisfactorily with a wide range of syngas composition. For methane production, the feedstock ideally should

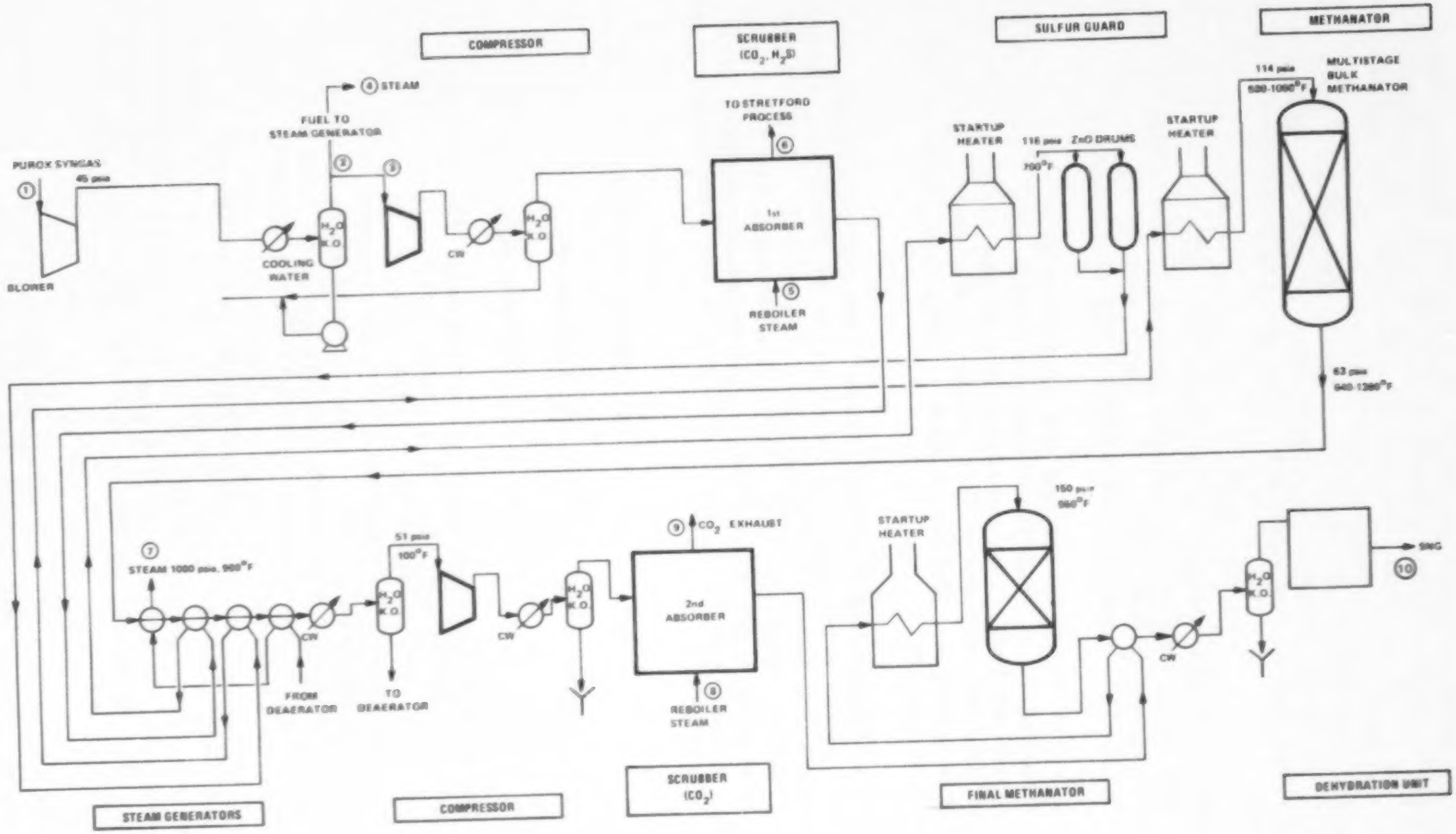

COMPRESSOR
SCRUBBER (CO$_2$, H$_2$S)
SULFUR GUARD
METHANATOR
PUROX SYNGAS
①
45 psia
BLOWER
COOLING WATER
FUEL TO STEAM GENERATOR
④ STEAM
②
③
H$_2$O K.O.
CW
H$_2$O K.O.
TO STRETFORD PROCESS
⑥
1st ABSORBER
⑤
REBOILER STEAM
STARTUP HEATER
116 psia
700°F
ZnO DRUMS
STARTUP HEATER
114 psia
500-1000°F
MULTISTAGE BULK METHANATOR
63 psia
940-1380°F
⑦
STEAM 1000 psia, 900°F
CW
FROM DEAERATOR
H$_2$O K.O.
51 psia
100°F
TO DEAERATOR
CW
H$_2$O K.O.
⑨ CO$_2$ EXHAUST
2nd ABSORBER
⑧
REBOILER STEAM
STARTUP HEATER
150 psia
900°F
CW
H$_2$O K.O.
SNG
⑩
STEAM GENERATORS
COMPRESSOR
SCRUBBER (CO$_2$)
FINAL METHANATOR
DEHYDRATION UNIT

Figure C-1. Methanation process for syngas.

TABLE C-1A. METHANATOR FLOW STREAMS* (SI UNITS)

Stream number	Stream	Quantity	Other information
1	Purox Gas	753×10^3 Nm^3/d 14.57 MJ/Nm^3 10.94 TJ/d	Saturated with water vapor at 38°C
2	Purox Gas to Steam Generator	133×10^3 Nm^3/d	Saturated with water vapor at 38°C
3	Purox Gas to be Processed	620×10^3 Nm^3/d	
4	Packaged Boiler Steam	21 764 Mg/h	6 894 kPa, 482°C Blowdown 2 268 kg/h
5	Reboiler Steam, 1st Absorber	10 873 kg/h	Exhaust steam 44 kPa
6	CO_2 & H_2S to Stretford Unit	CO_2 - 11 698 kg/h H_2S - 14 kg/h	Stretford process produces pure sulfur
7	Steam Generation/ methanator train	21 247 kg/h	6 894 kPa, 482°C
8	Reboiler Steam, 2nd Absorber	19 632 kg/h	448 kPa
9	CO_2 from 2nd Absorber	21 092 kg/h	
10	Product Gas, SNG	220×10^3 Nm^3/d 36.51 MJ/Nm^3 8.02 TJ/d	CH_4 - 91.2% by vol. H_2 - 1.2% CO - 400 ppm CO_2 - 4.0% N_2 + Ar - 3.6%

*Based on calculations at Parsons for nominal raw refuse capacity of 1360 Mg/d.

TABLE C-1B. METHANATOR FLOW STREAMS*
(ENGLISH UNITS)

Stream number	Stream	Quantity	Other information
1	Purox Gas	28.03×10^6 dry scf/d 370 Btu/scf 10.37×10^9 Btu/d	Saturated with water vapor at 100°F
2	Purox Gas to Steam Generator	4.95×10^6 dry scf/d	Saturated with water vapor at 100°F
3	Purox Gas to be processed	23.08×10^6 dry scf/d	
4	Packaged Boiler Steam	47,980 lb/hr	1000 psia, 900°F Blowdown 5000 lb/hr
5	Reboiler Steam, 1st Absorber	23,970 lb/hr	Exhaust steam 65 psia
6	CO_2 & H_2S to Stretford Unit	CO_2 - 25,770 lb/hr H_2S - 30 lb/hr	Stretford process produces pure sulfur
7	Steam Generation/ methanator train	46,840 lb/hr	1000 psia, 900°F
8	Reboiler Steam, 2nd Absorber	43,280 lb/hr	65 psia
9	CO_2 from 2nd Absorber	46,500 lb/hr	
10	Product Gas, SNG	8.2×10^6 scf/d 927 Btu/scf 7.60×10^9 Btu/day	CH_4 - 91.2% by vol. H_2 - 1.2% CO - 400 ppm CO_2 - 4.0% N_2 + A - 3.6%

*Based on calculations at Parsons for nominal raw refuse capacity of 1500 TPD.

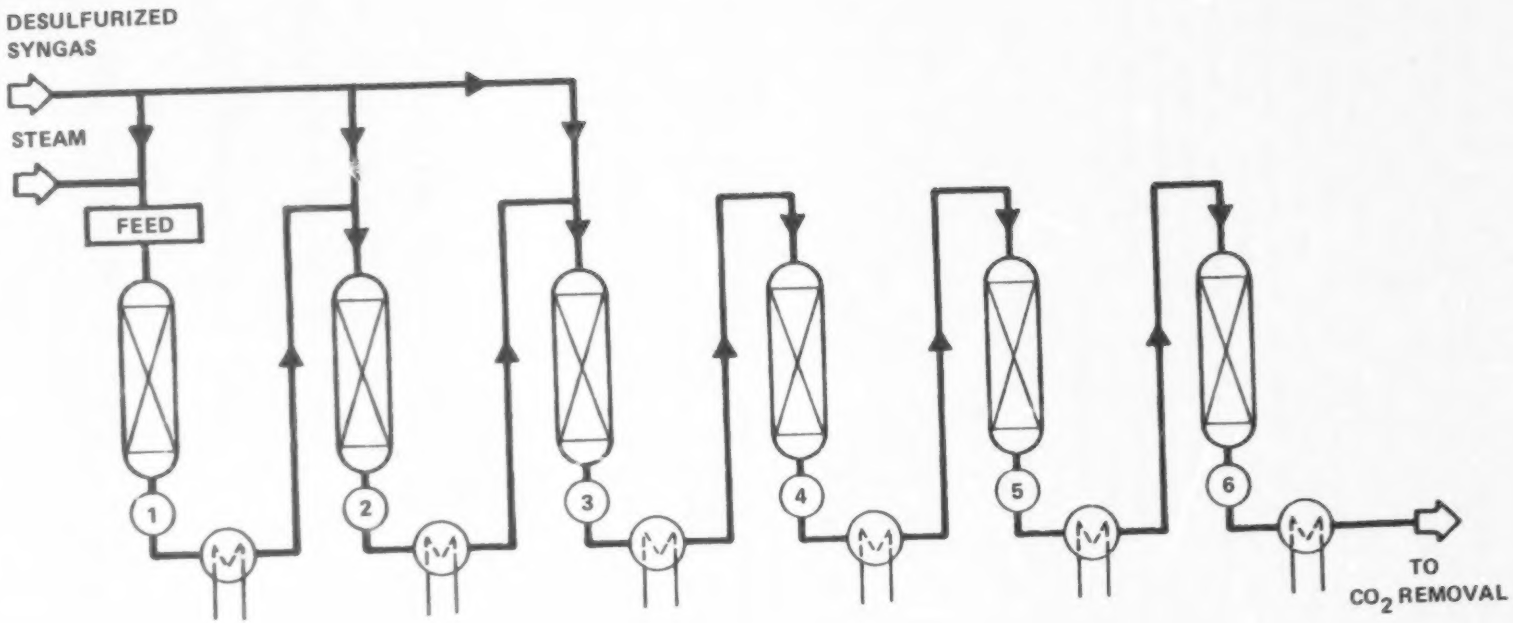

DESULFURIZED SYNGAS
STEAM
FEED
1
2
3
4
5
6
TO CO_2 REMOVAL

Figure C-2. Process schematic for bulk methanation.

contain six times as many hydrogen atoms in the form of hydrogen gas or water as there are carbon atoms in the form of carbon monoxide. The model syngas is relatively low in hydrogen and high in carbon monoxide, which means that a large amount of process steam must be used. Further, the relatively large carbon dioxide component in the feed gas requires proportionate amounts of steam for absorption-liquid regeneration. Certain other petroleum and coal partial-oxidation processes producing hot gases, in addition to the methanation process, normally yield enough steam for both process requirements and for driving the compression equipment with steam turbines. With cold gases from a pyrolysis system, however, a portion of the syngas is required to generate steam. The amount of process and stripping steam required dictates the rate of steam production. High pressure steam is produced at 6 894 kPa (1000 psia) and 482°C (900°F), then expanded to process pressure levels through turbines to provide the power requirements of the system. The quantity of syngas diverted to steam generation is 18% of the Purox system production. More high pressure steam is produced than is usable for driving compressors. Therefore, a turbo-electric generator is used to generate electric power and backpressure steam is used for the reboilers.

The SNG produced has the following composition by volume: CH_4, 91.2%; H_2, 1.2%; CO, 400 ppm; CO_2, 4.0%; N_2 + Ar, 3.6%. Moisture is removed so that the gas has a dew point of -40°C (-40°F). The HHV of the SNG is 36.51 MJ/Nm^3 (927 Btu/SCF) and is produced at the rate of 220 x 10^3 Nm^3/d (8.2 x 10^6 SCF day) or 8.02 TJ/d (7.60 x 10^9 Btu/day).

Because a commercial-scale plant using this process has not been built, accurate detailed costs are not available. Estimates were made based on preliminary design studies. No commercial scale methanator system of any kind has been built for producing pipeline gas from a synthesis gas.

In generating steam for use in the process, that steam used in a turbo-electric generator produces 1700 kW. The following is a listing of steam turbine drives:

	Steam Rate		
	kg/h	lb/hr	
Purox gas blower	7 022	15,480	- 1022 kW (1370 HP) (Drive)
Feed Compressor	16 774	36,980	- 2283 kW (3060 HP) (Drive)
Product Compressor	3 856	8,500	- 574 kW (770 HP) (Drive)
Turbo-Electric Generator	15 359	33,860	- 2110 kW (produced)
	43 010	94,820	

Various electric power drives for pumps and other devices require 330 kW. Boiler makeup amounts to 2087 kg/h (4,600 lb/hr). Cooling tower water flow is 20 m^3/min (5300 gpm) and its makeup is 3.8 percent.

A daily energy balance on the methanator process shows:

Energy in gas feedstock = 10.94 TJ (10.37 x 10^9 Btu)

Energy in product = 8.02 TJ (7.60 x 10^9 Btu)

$$\left.\begin{array}{ll}\text{Equivalent heat in electric power generated} & = 0.54\ \text{TJ}\ (0.51 \times 10^9\ \text{Btu}) \\ \text{Electric drives} & = 0.08\ \text{TJ}\ (0.08 \times 10^9\ \text{Btu})\end{array}\right\}\ \text{net}=0.43\text{x}10^9\ \text{Btu}$$

The conversion efficiency for the methanator is

$$\frac{7.6}{10.37} \times 100 = 73.3\%$$

Similarly, for the syngas plant plus methanator it is

$$\frac{7.6}{13.89}\ (100) = 54.7\%$$

The overall plant net thermal efficiency, accounting for energy required to operate the plant, is determined to be

$$\frac{7.6 + 0.51 - 0.08 - 0.25 - 2.82}{13.89} = 35.7\%$$

METHANE CONVERSION CONSTRUCTION AND OPERATING COSTS

Addition of a methanator system to the gasifier plant increases the complexity. Methanators have not been operated in commercial sizes with Purox-like gases, which leads to a lower probable utilization factor. Over 92% utilization factor on a yearly basis was used for producing the Purox gas because of redundancy in equipment. With addition of a methanator system, a value of 85% is used for the entire plant. This results in 422 Gg/y (465,000 TPY) of raw refuse that can be processed and 68.0 x 10^6 Nm^3/y (2.54 x 10^9 SCFY) of product methane.

Capital Cost

Capital cost for a complete solid waste-to-methane facility would start with the syngas production facility (front-end plus gasifier) described in the Purox Section. Added to this is the methanator cost shown in Table C-2.

The methanator should be located adjacent to the Purox plant with a pipeline required for connection to the nearest natural gas main pipeline. Land required for the methanator is approximately 20 200 to 24 300 m^2 (5 to 6 acres). Electric power required is 330 kW, but 1700 kW will be generated by the excess high quality steam in the plant. Compressors will be steam driven from plant steam generators. Water supply will be approximately 1500 dm^3/min (400 gpm).

TABLE C-2. ESTIMATED CAPITAL COST REQUIREMENTS FOR METHANE (1975 DOLLARS)

Item	Cost ($ millions)
Construction	
Front end and syngas plant	53.75
Methanation Plant	15.00
Interest During Construction (8-1/2% one year)	5.84
Startup Costs	3.27
Working Capital (25% of annual operating cost)	2.07
Total	79.93

The construction cost is estimated at $15 million for the methanator, which is considerably less than either the ammonia or methanol plant because of much lower operating pressures and less gas treatment. The total plant capital cost given in Table C-2 is $79.93 million with a construction cost of $68.75 million.

Operating Costs

Operating costs are shown in Table C-3. Labor costs includes operating labor only, with maintenance including the maintenance labor. A credit is taken for electric power because of the large amount of steam generated for reboiler and process use. Not all the steam could be used in drive turbines for compressors; therefore, a steam-electric generator unit was included to generate 2110 kW, of which 350 kW was used for various small electric motors, and the remainder is fed to the Front End/Purox systems. The amount in excess is 1760 kW and over a year this amounts to 13.1 x 10^6 kWh, or $328,000 based on 25 mills/kWh. The same price for electrical power was used in the syngas plant and therefore the effect is the same as reducing the amount of power purchased from a utility.

The operating cost per ton of raw refuse, based on a yearly operating schedule, is $19.55/Mg ($17.74/ton) of raw refuse or $3.30/GJ ($3.49/million Btu).

Economic Analysis

The effect on net SNG costs of receiving varying drop charges is shown in the table below. In each case it is assumed that revenues of $331/Mg ($300/ton) of aluminum and $44/Mg ($40/ton) of steel are received. Unit

TABLE C-3. ANNUAL OPERATING COSTS FOR METHANE (1975 DOLLARS)

Item	Cost/year ($000)
Methane Unit	
Labor	350
Power	(328)*
Maintenance	750
Production Materials	320
Water	145
Total (Methane unit only)	1237
Front End & Gasifier (Table 43)	7016
Total Plant	8253

*The methanator has excess power, but the credit taken has been charged to the Front End and Gasifier and is included in the $7,016,000 shown.

capital costs for the $79.93 million facility are $20.00/Mg ($18.15/ton) of raw refuse or $3.39/GJ ($3.58/10^6 Btu) of gas produced. Unit operating costs are $19.55/Mg ($17.74/ton) of refuse and $3.32/GJ ($3.50/10^6 Btu).

NET COSTS TO PRODUCE SNG

	Raw Refuse Basis		Energy Basis	
Drop Charge	Per Mg	Per Ton	Per GJ	Per 10^6 Btu
0	$34.66	$31.44	$5.88	$6.20
$ 5.51/Mg ($5.00/ton)	29.14	26.44	4.95	5.22
$11.02/Mg ($10.00/ton)	23.63	21.44	4.01	4.23

It is roughly estimated that SNG produced from coal or LNG transported from a proposed plant in South Alaska, Indonesia, or North Africa will sell for $3 to $4 per million Btu or higher in 1975 dollars. This indicates that SNG manufactured from solid waste could be competitive with other new sources of SNG or natural gas provided a sufficiently high drop charge is available.

ELECTRIC POWER FROM GAS TURBINE COMBINED CYCLE PROCESS DESCRIPTION

In the combined cycle, use is made of a gas turbine operating in series with a waste-heat boiler and a steam turbine. Hot exhaust gases from the gas turbine are a means of producing steam from a waste heat boiler. Previous studies (Ref. C-1) showed that other cycle schemes with gas turbines would result in a lower capital cost, but the combined cycle is thermodynamically the most efficient and results in the least cost per kWh of net electric power produced.

Data were developed using specifications for two actual gas turbine/generator assemblies; both units can operate with either gas or liquid fuel. The gases include syngas or natural gas, while the liquids include petroleum distillates or methanol. Because of the low heating value per unit volume of the syngas, the units must be started and brought to operating temperatures on diesel fuel oil. The unit can be set up to burn gas and oil simultaneously with the oil automatically increasing to maintain full generator output if the gas supply varies, is inadequate, or stops, and a power network emergency arises. In this way, the units can be kept operating at full capacity. Since startup oil facilities are required in any case, this capability increases the cost of the installation only by the amount of additional fuel oil storage required to support continuous oil operation.

A layout of a combined cycle plant is shown in Figure C-3. Fuel gas must be compressed to about 1724 kPa (250 psi) to feed the two gas turbines, consuming about 5 kW of power when one module is operating at full capacity. For simplicity, an electric-driven centrifugal compressor is used to pressurize the feed gas. The heat rate for this combined cycle is approximately 12.55 MJ (11,900 Btu)/kWh. The net nominal capacity of a module is 29 MW. Net production of power to the bus was found to be 36.3 MW for a 1361 Mg/d (1,500 TPD) plant and subtracting the power to drive the syngas plant (11.2 MW) leaves 25.1 MW to a customer.

ELECTRIC POWER FROM GAS TURBINE COMBINED CYCLE CONSTRUCTION AND OPERATING COSTS

Other equipment arrangements than given here using a gas turbine have been studied with respect to capital and operating costs and cost per unit output. Cases that were studied (Ref. C-1) included combined cycle, gas turbine only, gas turbine plus steam generation, and steam generation only. Capital costs for the combined cycle were highest but, because it was most thermodynamically efficient, it produced electric power at the least cost per kWh even where other systems had a credit for steam sales. The combined cycle was chosen for further analysis and the costs are given in the following text.

This technology is well-known with standard equipment. Costs are based on passing 751 x 10^3 m^3/d (28.03 x 10^6 SCFD) of syngas to the combined cycle plant. It is estimated that there will be two weeks of scheduled downtime at the same time as that with the syngas system plus one week of unscheduled shutdown in addition to the two weeks for the syngas system. Thus 47 of the

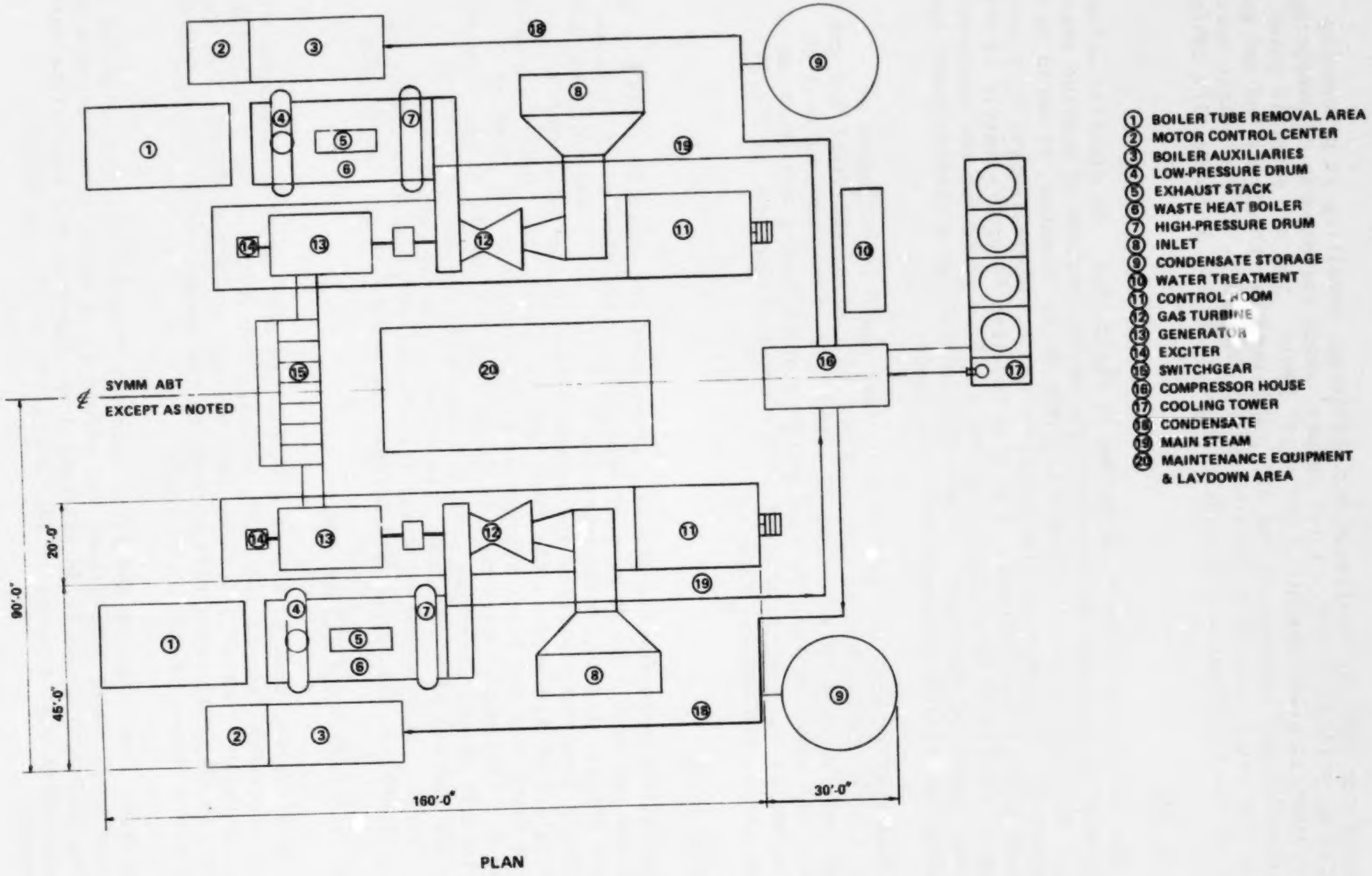

① BOILER TUBE REMOVAL AREA
② MOTOR CONTROL CENTER
③ BOILER AUXILIARIES
④ LOW-PRESSURE DRUM
⑤ EXHAUST STACK
⑥ WASTE HEAT BOILER
⑦ HIGH-PRESSURE DRUM
⑧ INLET
⑨ CONDENSATE STORAGE
⑩ WATER TREATMENT
⑪ CONTROL ROOM
⑫ GAS TURBINE
⑬ GENERATOR
⑭ EXCITER
⑮ SWITCHGEAR
⑯ COMPRESSOR HOUSE
⑰ COOLING TOWER
⑱ CONDENSATE
⑲ MAIN STEAM
⑳ MAINTENANCE EQUIPMENT & LAYDOWN AREA
℄ SYMM ABT
EXCEPT AS NOTED
90'-0"
20'-0"
45'-0"
160'-0"
30'-0"
PLAN

Figure C-3. Layout of combined cycle electric power plant.

52 weeks per year are available for operation, resulting in processing 477 703 Mg/y (493,500 TPY) of raw refuse, which corresponds to producing a net electric power output of 200 x 10^6 kWh/y. The net electric power accounts for gas compression and all power needs in the front end and gasifier units; the latter two units require 88.3 x 10^6 kWh/y. The electric energy required for the front end and gasifier units is 197.3 kWh/Mg (179 kWh/ton).

Capital Cost

The essential equipment is listed in Figure C-3. An electric drive is recommended to compress the pyrolysis gas mainly because of startup requirements. With the syngas discharged at atmospheric pressure, it would be best to locate the compressor at the gas plant and transport the gas by a small diameter pipe to the turbines. The land required is approximately 12 000 m^2 (3 acres) and the plant produces its own electric power for the compressor and other parts of the plant. There will be need for a utility power line to the plant for startup purposes and other needs.

Construction cost of the electric power plant is estimated at \$16.21 x 10^6; adding this to the construction cost of the front end and Purox systems results in a total of \$69.96 x 10^6. The total capital cost of \$79.96 x 10^6 shown in Table C-4 includes interest during construction (equivalent to one year's interest on the construction cost at 8-1/2%), startup costs, and working capital.

Operating Costs

Operating costs for the electric power unit are shown in Table C-5 as \$1,236,000 per year. No power cost appears as with other plants because electric motors, lights, instruments and controls, etc., are supplied with electricity from the generator and accounted for in the net output of 25.1 MW (11.1 MW are used in the front end and gasifier). Operating costs from the front end and Purox systems of \$7,016,000/year are shown in Section 8. Included in this cost is \$2,307,000 for power, which is deleted as explained. A net operating cost for the front end and gasifier is \$4,709,000 instead of \$7,016,000. The total operating cost is then \$5,945,000/yr. Unit operating costs for the entire plant (raw refuse to electric power) is \$13.27/Mg (\$12.04/ton) raw refuse or 29.7 mills/kWh.

ECONOMIC ANALYSIS FOR ELECTRIC POWER

With a capital cost of \$79.96 million, the unit amortization costs for the electric power case is \$18.87/Mg (\$17.12/ton) refuse or 42.2 mills/kWh. With an operating cost of \$13.27/Mg (\$12.04/ton) or 29.7 mills/kWh, the total unit cost is thus \$32.14/Mg (\$29.16/ton) of raw refuse or 71.9 mills/kWh to produce a net output of 200 x 10^6 kWh/y.

Revenues from aluminum and steel recovery from 447 703 Mg/y (493,500 TPY) raw refuse is \$4.90/Mg (\$4.45/ton) raw refuse or 11 mills/kWh. Revenues from \$11.02/Mg (\$10/ton) or \$5.51/Mg (\$5/ton) drop charge on the raw refuse results in an equivalent unit revenue of 24.7 mills/kWh or 12.3 mills/kWh, respectively.

TABLE C-4. ESTIMATED CAPITAL COST FOR ELECTRIC POWER

Item	Cost ($ million)
Construction	
Front-End Processing and Syngas Plant	53.75
Gas Turbine - Combined Cycle Plant	16.21
Interest During Construction (8-1/2% one year)	5.95
Startup Costs	2.56
Working Capital	1.49
Total Plant	79.96

TABLE C-5. ESTIMATED OPERATING COST FOR ELECTRIC POWER

Item	Cost ($000)
Electric Power:	
Labor	499
Power	-
Maintenance	457
Production Materials	138
Water	142
Total Electric Power	1,236
Front-End and Purox System (Table 43 less electric power)	4,709
Total Plant	5,945

The net cost is the total cost less drop charges and metal sales given above. For the highest drop charge case, the net cost is \$16.21/Mg (\$14.71/ton) raw refuse and for the \$5/ton drop charge case, the net cost is \$21.73/Mg (\$19.71/ton) raw refuse. For zero drop charge, the net cost is \$27.24/Mg (\$24.71/ton). The corresponding costs per unit net electrical power output is 36.2 mills/kWh, 48.6 mills/kWh, and 60.9 mills/kWh, respectively. It should be noted that the price of electric power used in this report is 25 mills/kWh, less than the cost of producing it with the system evaluated here. In many regions of the U.S. the present cost of electric power is greater than 30 mills/kWh. With drop charges greater than \$10/ton, this type of plant would be economically acceptable in those regions.

CONVERSION TO FUEL GRADE METHANOL PROCESS DESCRIPTION

The purpose of utilizing pyrolysis gas for synthesis of a fuel grade methanol is to produce a storable and more transportable fuel. One possible application is peaking power gas turbine-electric power generators used by utilities (Ref. C-4). Replacement of petroleum distillate fuel by methanol requires careful economic analysis. Another application is for internal combustion engine use. Although isolated tests have shown some potential, it is not clear that widespread practical application would be possible. Fuel grade methanol is quite miscible with gasoline because of impurities present (Ref. C-5).

The CO and H_2 in the model syngas (in the ratio of 5:3) can be converted to methanol by first using a water-gas shift reaction in a catalyst bed so that the mole ratio of CO to H_2 in the gas is slightly less than 1:2, and then passing this mixture at high pressure through another catalyst bed. The basic reactions are:

$$CO + H_2O \rightarrow H_2 + CO_2$$

$$CO + 2H_2 \rightarrow CH_3OH$$

Also, after scrubbing, CO_2 is present in a 1:20 ratio to CO and will react with H_2 as follows:

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

Figure C-4 shows a typical process schematic. First, both H_2S and CO_2 are removed from the syngas. After stripping from the absorbent, the H_2S is converted to sulfur by means of the Claus Process. An alternative method for sulfur recovery is the Stretford process. The desulfurized gas is then passed into a shift converter with steam to adjust the CO/H_2 mole ratio. The CO_2 in the gas after shift converter action is removed by absorption and stripping towers. Water vapor is removed in a condenser before the CO/H_2 gas mixture is passed in the compressor. The pressure is then raised to either the low range of 5.1 MPa (50 atmospheres) or the high range of 10.2 to 15.3 MPa (100 to 150 atmospheres), depending on the catalyst chosen. The higher pressure produces a higher yield, but economics will dictate the final choice. Methanol synthesis takes place on a zinc/chromium oxide catalyst or a

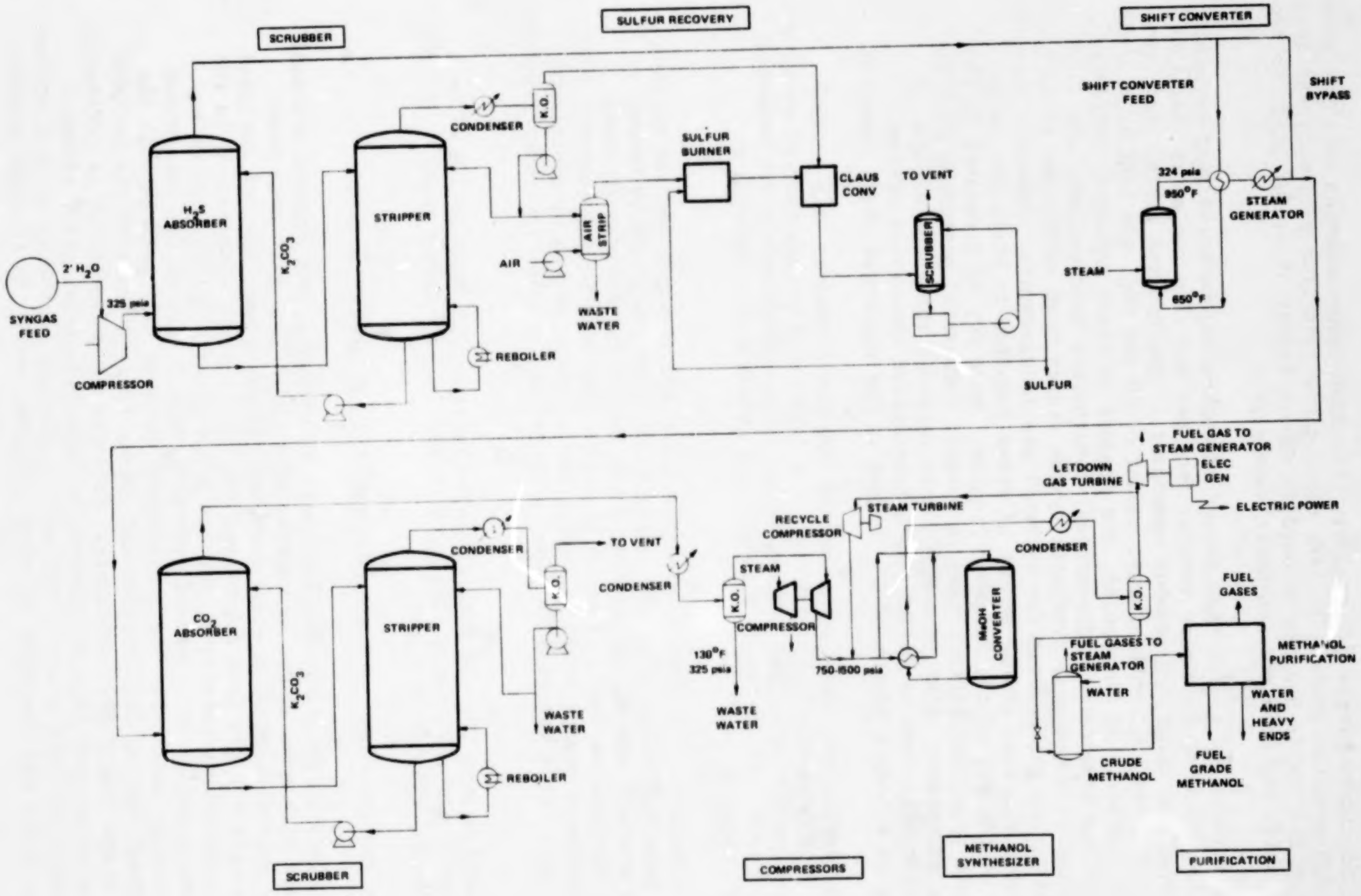

SCRUBBER
SULFUR RECOVERY
SHIFT CONVERTER
SHIFT CONVERTER FEED
SHIFT BYPASS
CONDENSER
K.O.
SULFUR BURNER
CLAUS CONV
TO VENT
324 psia
950°F
STEAM GENERATOR
H_2S ABSORBER
K_2CO_3
STRIPPER
AIR STRIP
AIR
SCRUBBER
STEAM
650°F
2' H_2O
325 psia
SYNGAS FEED
COMPRESSOR
REBOILER
WASTE WATER
SULFUR
FUEL GAS TO STEAM GENERATOR
LETDOWN GAS TURBINE
ELEC GEN
ELECTRIC POWER
STEAM TURBINE
RECYCLE COMPRESSOR
CONDENSER
TO VENT
CONDENSER
K.O.
STEAM
COMPRESSOR
130°F
325 psia
WASTE WATER
750-1500 psia
MeOH CONVERTER
K.O.
FUEL GASES
FUEL GASES TO STEAM GENERATOR
WATER
METHANOL PURIFICATION
WATER AND HEAVY ENDS
CRUDE METHANOL
FUEL GRADE METHANOL
CO_2 ABSORBER
K_2CO_3
STRIPPER
K.O.
REBOILER
WASTE WATER
SCRUBBER
COMPRESSORS
METHANOL SYNTHESIZER
PURIFICATION

Figure C-4. Synthesis process for methanol.

copper/zinc/chromium type of catalyst. The zinc/chromium oxide catalyst used in the high-pressure process is less susceptible to sulfur poisoning and less costly. A zinc oxide bed can be used to remove traces of sulfur gases to protect the shift and methanol synthesis catalysts.

The synthesized gas is then passed through a regenerative heat exchanger to heat the incoming catalytic reactor feed gas and then cooled to condense the methanol and other hydrocarbon components. Uncondensed gases, particularly N_2, Ar, and CH_4, with a small amount of CO and CO_2, are sent to a steam generator furnace. At this point, the product is crude methanol containing higher boiling oxygenated hydrocarbons, condensible hydrocarbons, and water. One licensor of a methanol synthesis system states that sufficient steam is generated within the process for internal use requirements. However, this is questionable, because of the amount of steam required to strip the large quantity of CO_2 out of the scrubber liquids. More CO_2 is generated in the solid waste pyrolysis process than in current commercial petroleum partial-oxidation processes. Also, the H_2/CO mole ratio in the Purox off-gas is smaller than that from petroleum partial-oxidation conversion systems, resulting in a larger amount of CO_2 formed in the water-gas shift reaction.

Upon leaving the condenser after the synthesis reactor, the crude methanol is approximately 85% methanol. A dewatering column removes water and heavy ends, producing a fuel-grade methanol with approximately 92% methanol, 5% hydrocarbons, and 3% higher alcohols and esters with a density of 0.80 g/cm^3 (6.67 lb/gal).

Approximately 11 100 kW of electric power are required for the methanol unit. A detailed design of a unit using Purox-type gas would be needed to determine whether some of the driving power can be furnished with steam generated for process use. If steam is to be used for the compressors, then a steam generator source would be needed for startup, adding an additional expense. Until this analysis is done, a conservative value for power required is used.

Production rate for the fuel-grade methanol is 222 Mg/d or 278 m^3/d (245 TPD or 73,500 GPD) for a 1361 Mg/d (1,500 TPD) of refuse plant. The HHV is 19.93 MJ/dm^3 (71,500 Btu/gal).

CONVERSION TO FUEL GRADE METHANOL CONSTRUCTION AND OPERATING COSTS

Technology is available for synthesis of methanol, but because methanol plants start with natural gas or naphtha as feedstocks, which have been thoroughly decontaminated, present methanol process plants are not designed to operate with the gas from Purox-type systems. Certain impurities in the gas could contaminate catalysts, and the large amount of hydrocarbons may require consideration of a type of reforming unit. Parsons has determined on a preliminary basis that the hydrocarbons present will pass through the system without causing difficulties and appear in solution with the methanol as a fuel grade liquid (92% methanol). Presence of hydrocarbons is ordinarily undesirable in the purification process to make industrial grade methanol (99.85% pure), but this grade is for use in chemical synthesis or as a solvent and not for fuel, and therefore is of no interest here. An in-depth process engineering and facilities study is required to determine more accurately the details of the plant and associated costs. Presented are costs based on past experience in methanol manufacture.

The costs are based on production from a 1361 Mg/d (1,500 TPD) plant. With a methanol plant added to the syngas plant, the utilization factor is assumed to decrease from the 92% to approximately 88%, resulting in processing 482,000 TPY of raw refuse and producing 78,700 TPY (23.83 x 10^6 GPY) of fuel grade methanol.

Capital Cost

Capital cost for a complete solid waste to methanol facility would start with the front end and Purox facility described in Section 8; this is added to the methanol facility cost as shown in Table C-6.

The methanol plant should be adjacent to the syngas facility. Land required for the methanol unit is 20 200 to 24 300 m^2 (5 to 6 acres), which will include storage of methanol. This tank could be a small surge type with a pipeline to a customer not too distant from the plant. As mentioned previously, a likely customer is a utility with peaking power gas turbines using distillate fuel. In the TVA power system, as an example, peaking turbines operate one to three hours per day. Storing methanol at the turbine site and using a 24-hour production in two hours of combustion, a gas turbine-electric power generation plant with 220 MW capacity can be operated intermittently in a peaking power schedule.

The construction cost for the methanol plant in 1975 dollars is approximately $26.12 million. Total capital costs required are given in Table C-6.

Operating Costs

Operating costs are shown in Table C-7 with details for the methanol unit and addition of the operating cost for the front-end and Purox units. Labor includes only operating labor, and maintenance labor is included in the Maintenance item. There are some disagreement on the amount of outside power required from different licensors of the process. To be conservative, a power level of 11 000 kW was used in the methanol unit. Water costs include effluent discharge fees. The total operating cost for the plant (from raw refuse to fuel grade methanol) is $11,372,000 per year. This results in a unit cost of $26.01/Mg ($23.60/ton) raw refuse, or $159.28/Mg ($144.50/ton) of fuel grade methanol (47.7¢/gal, $6.67/$10^6$ Btu).

ECONOMIC ANALYSIS FOR METHANOL PLANT

The methodology for arriving at the probable range of net costs for a syngas-derived fuel has been sufficiently developed previously that details for the methanol case need not be cited here. The concluding summary Table C-10 contains the results of the calculations made. For the standard case of the $11.02/Mg ($10/ton) drop charge, the net cost would be $0.15/$dm^3$ or $7.69/GJ ($0.58/gallon or $8.11/$10^6$ Btu). It must be concluded, if

TABLE C-6. ESTIMATED CAPITAL COST FOR METHANOL

Item	Cost ($ million)
Construction	
Front End Processing & Syngas Plant	53.75
Methanol Conversion Plant	26.12
Interest During Construction	2.22
Startup Costs	4.21
Working Capital	2.84
Total	89.14

TABLE C-7. ANNUAL OPERATING COSTS FOR METHANOL

Item	Cost $(000)
Methanol Unit	
Labor	400
Power	2,120
Maintenance	1,130
Production Materials	506
Water	200
Total, Methanol Unit	4,356
Front End & Purox System	7,016
Total Plant	11,372

economics is the sole criterion, that fuel grade methanol costs appear too high for most regions to consider.

If there is a desire to use this grade methanol for automobiles, its cost must be compared with gasoline costs. For a retail price of gasoline at \$0.60/gal, the equivalent price is approximately $\$5.20/10^6$ Btu as compared to the net cost of fuel grade methanol cited above of $\$8.11/10^6$ Btu. If a manufacturer's profit and distribution costs are included, the fuel grade methanol's retail price will be quite high and would not be competitive with present retail gasoline prices even with a higher drop charge.

Other factors are needed to make a final decision on the use of methanol, such as cost of changes to make methanol compatible with present automobile engines, reduction in emission controls, costs needed for separate storage at service stations, and the cost of preventing injury due to the high toxicity of methanol vapors.

CONVERSION TO AMMONIA PROCESS DESCRIPTION

Conversion of syngas to ammonia has been seriously considered in several studies because of the high monetary value of anhydrous ammonia primarily used as a fertilizer or as a fertilizer base. High prices for ammonia, along with a high refuse drop charge (\$12/ton refuse) has led Seattle to consider the building of a solid waste-to-ammonia system as possibly economically feasible. For cities with drop-charges of \$2 to \$4 per ton, the revenues are insufficient to allow selling of ammonia at the market price. The market price of ammonia has recently varied from \$100 to \$180/ton. This is bulk sale price to a distributor.

Ammonia synthesis requires quite pure nitrogen and hydrogen which, when mixed in the ratio of one mole N_2 and three moles H_2 and passed through a catalytic bed at approximately 34.5 MPa (5,000 psi) and about 538°C (1000°F), results in the production of two moles of NH_3. Modern synthesis plants can convert approximately 94% of the nitrogen and hydrogen mixture to ammonia. The reaction equation is:

$$N_2 + 3H_2 = 2NH_3$$

Each plant design may be different in terms of gas compression, cleanup, and conditioning. In recent years, more attention has been paid to utilizing equipment requiring less energy with more heat recovery because of the large amount of power needed to drive the compressors and the large amount of process steam required for the water-gas shift reactor and reboiler steam for stripping of acid gases. Attention must be paid to the detailed design to minimize use of hydrocarbons as compared to that produced from natural gas or naphtha steam reformers and high temperature partial-oxidation steam systems that essentially convert all hydrocarbons. An ammonia plant has not yet been built using gases such as those from Purox or a Lurgi coal gasifier. Furthermore, each new gasifier or feedstock produces trace impurities that may be deleterious to catalysts. A number of plants have been built for coal gasification to ammonia, but some of these are no longer in operation (Ref. C-6).

Examples of partial-oxidation systems are the Koppers-Totzek, Texaco, and Shell processes (Ref. C-7). If a gas cleanup and treating scheme is designed for the Purox gas, a pilot unit must be built and tested with the actual gases from the demonstration plant at South Charleston. The gas conditioning process has been and will continue to be a subject of research and development.

In the design of the ammonia plant, a major effort will need to be directed at converting pyrolysis gas to a pure H_2 stream. Several routes are possible in gas treating. An important item is to use as much of the hydrocarbons in the gas as a source of hydrogen. Therefore, a steam reforming unit, not previously used in partial oxidation of oil or coal, is considered for the system. Use of a reformer to convert the hydrocarbons in the off-gas from a Lurgi gasifier to CO and H_2 has been discussed (Ref. C-8).

There are several choices in treating the syngas. Each requires an acid gas scrubber initially, and then in the subsequent processing it is necessary to make choice of one of the following processes:

1. Removal of the hydrocarbons as a separate stream in the purification step and then steam reform them (heavy hydrocarbons will not reform)
2. Passage of all the gas through a steam reformer that will not convert the heavier hydrocarbons.
3. Passage of all the gas through a reformer-methanator that produces CH_4, which is then steam reformed.
4. Passage of all the gas through a cryogenic fractionator to separate the components and steam reform the lighter hydrocarbons (German Linde).

These schemes are expensive and can increase considerably the cost of existing types of ammonia processes. Shown in Figure C-5 is the type of ammonia plant considered here, one that uses a liquid nitrogen wash for final purification of the gas to be synthesized to NH_3.

For present purposes, approximately 10% of the gas input, along with one-third of the hydrocarbon gas, is considered necessary to provide sufficient process steam and heat for the ammonia plant. This quantity should be more accurately determined during a preliminary engineering facility design phase. High purity nitrogen will be furnished from the oxygen plant, which is modified from that in which the product is oxygen only. There is more than sufficient N_2 available, but some will be in liquid form for use in the cryogenic hydrogen purification section.

A low-pressure compressor is used to pass the gas through an acid gas absorption system to remove H_2S, CO_2, and traces of HCl. Union Carbide reports finding 1 ppm or less of HCl in the Purox gas. The H_2S and CO_2 tail gas stream is then processed in a Stretford unit to produce sulfur, which is removed as a solid at the rate of approximately 3.6 Mg/d (4 TPD). The CO_2 is exhausted to the atmosphere at this point. The gas is then heated and passed

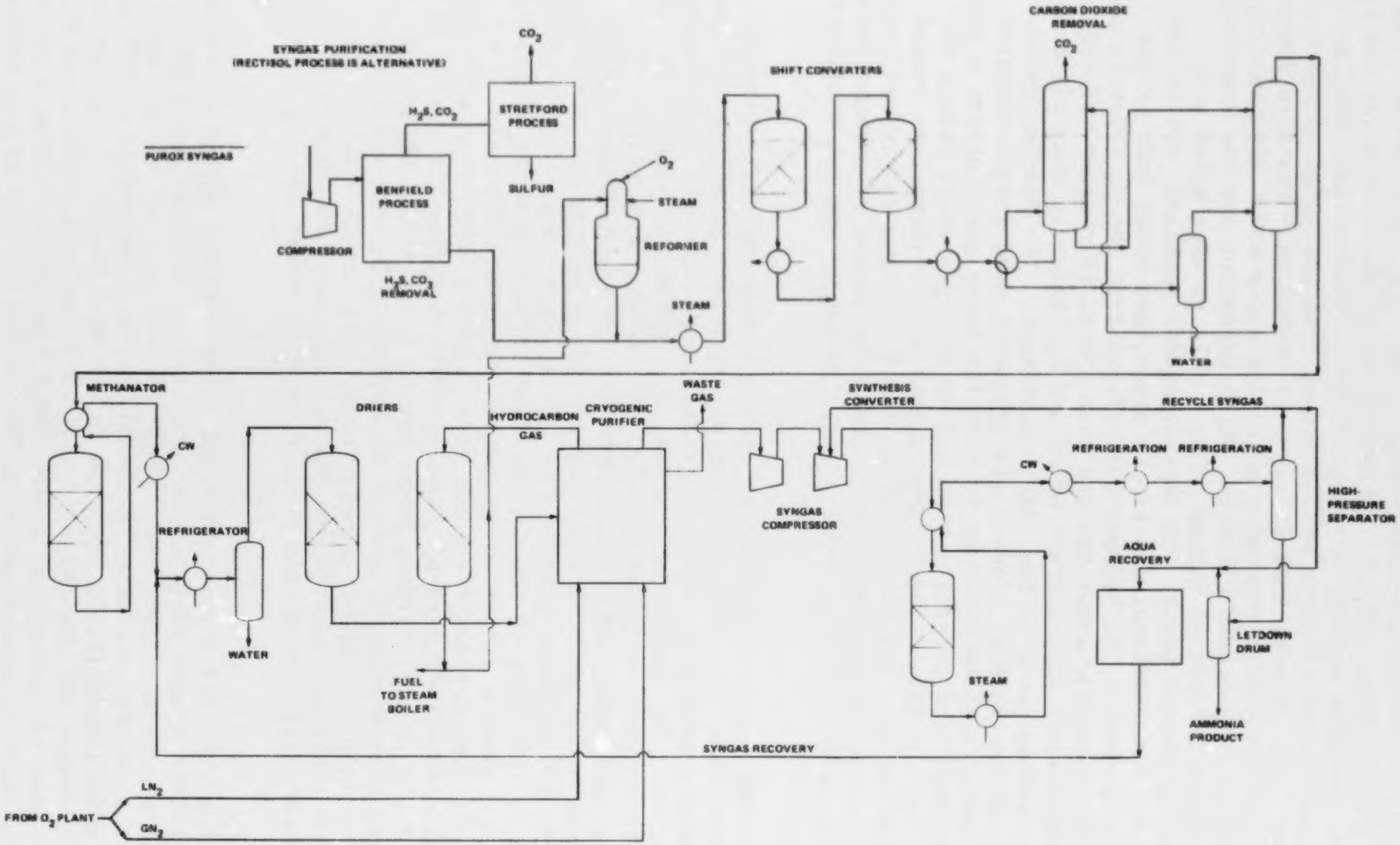

SYNGAS PURIFICATION
(RECTISOL PROCESS IS ALTERNATIVE)
PUROX SYNGAS
COMPRESSOR
BENFIELD PROCESS
H_2S, CO_2 REMOVAL
H_2S, CO_2
STRETFORD PROCESS
CO_2
SULFUR
O_2
STEAM
REFORMER
STEAM
SHIFT CONVERTERS
CARBON DIOXIDE REMOVAL
CO_2
WATER
METHANATOR
CW
REFRIGERATOR
WATER
DRIERS
FUEL TO STEAM BOILER
HYDROCARBON GAS
CRYOGENIC PURIFIER
WASTE GAS
SYNGAS COMPRESSOR
SYNTHESIS CONVERTER
STEAM
CW
REFRIGERATION
REFRIGERATION
RECYCLE SYNGAS
HIGH-PRESSURE SEPARATOR
AQUA RECOVERY
LETDOWN DRUM
AMMONIA PRODUCT
SYNGAS RECOVERY
FROM O_2 PLANT
LN_2
GN_2

Figure C-5. Flow diagram of ammonia plant.

through a water-gas-shift reactor to convert the CO and steam to hydrogen. Gas from the shift converter consists mostly of H_2, CO_2, hydrocarbons, and a small amount of CO. Next, the CO_2 is removed in an amine absorber and the gas then passed through a methanator where CO is reduced to less than 10 ppm. From here, the gas is cooled along with a stream from the purge of the final ammonia recovery tank. A good deal of water is condensed. For more complete dryness, the gases are passed through a molecular sieve bed. After drying, the gas is scrubbed with liquid nitrogen, which condenses out the remaining hydrocarbons leaving a purified stream of H_2. This is then mixed with gaseous N_2 from the oxygen plant. In this cryogenic purifier, 99% of the methane, all other hydrocarbons, 65% of the argon, and about half of the 10 ppm of CO are removed. The hydrocarbon off-gas from the purifier is used to regenerate the molecular sieve bed and then passed to a steam reformer to convert the hydrocarbons to a mixture of CO and H_2, which is then added to the main syngas stream going to the shift converters. The heavier hydrocarbons (C_4+) will not reform, however, in presently used steam reformers. The reason for using a steam reformer is that the Purox gas contains a good deal of hydrocarbons, and rejecting them all to fuel gas would reduce the ammonia output considerably. These hydrocarbons are in themselves needed feedstock for making H_2. The mixture of N_2 and H_2 is then compressed, using electric motor reciprocating compressors. With the amount of ammonia produced at less than 363 Mg/d (400 TPD), centrifugal compressors are not considered economically feasible.

The compressed gases, including recycled gas from the high-pressure ammonia separator tank, pass through a regenerative heat exchanger and then through the ammonia synthesis catalytic reactor tubes where N_2 is hydrogenated to produce ammonia. The exothermic heat of the reaction is removed in a steam generator. This steam is utilized in reboilers and for processing. The mixture of ammonia, hydrogen, and nitrogen from the reactor is cooled in the regenerative heat exchanger. With further cooling, the ammonia is condensed and the nitrogen and hydrogen mixture is recycled back through the reactors. A purge stream is sent back to the purification train to prevent a buildup of inert gases. The ammonia liquid is dropped in pressure and passed to a 18 144 Mg (20,000 ton) cryogenic storage tank. Such a large tank will allow storage of approximately 60 days of plant production during the period of low ammonia usage found in most farming areas during the winter. Choice of storage type and size depends on use of the ammonia. In some cases where a surge capability only is desired, storage under pressure in a sphere is desirable. Such tanks are built up to 454 Mg (500 tons) in capacity. This occurs where ammonia is transported by ship to areas where farming occurs all year.

A production rate for ammonia is based on an estimate of the probable amount of Purox-type syngas that can be converted to hydrogen and then to NH_3. If all the syngas were utilized, there would be 0.85 mole of NH_3 per mole of Purox gas which is equivalent to 0.34 ton NH_3 per ton raw refuse or 473 Mg/d (522 TPD) for a 1361 Mg/d (1,500 TPD) raw refuse feed plant. It is estimated that 10% of the syngas and one-third of the remaining hydrocarbons and H_2, not converted, are used for generating steam. This results in 0.58 mole NH_3 per mole of syngas, which is equivalent to 0.237 ton NH_3 per ton of raw refuse, or 323 Mg/d (356 TPD) NH_3 for the plant. A more optimistic estimate of the utilization of the hydrocarbons (only 20% for heating purposes) leads to 363 Mg/d (400 TPD) NH_3 for the plant. If all of the hydrocarbons are used for fuel (no reforming), then the production of ammonia would be approximately 227 Mg/d (350 TPD). Until a more detailed preliminary engineering design is made of the ammonia plant, a value of 323 Mg/d (356 TPD) NH_3 is used in determining the production cost of NH_3 for a 1361 Mg/d (1,500 TPD) raw refuse plant. If the production rate was based on the non-use of hydrocarbons, the revenues for ammonia would be 30% less than the base used herein.

CONVERSION OF SYNGAS TO AMMONIA CONSTRUCTION AND OPERATING COSTS

The costs presented here are approximations and reflect a great deal more uncertainty than the presentations for the front-end or the Purox facility. This is caused by the fact that the syngas of the composition produced has never been transformed to another product, and must be tested when catalysts are being used. The technology is available, but the unknown factor is the complexity, and so is, therefore, the cost of the specific facility required for the conversion process. This can only be determined by an in-depth chemical engineering process analysis of the required system.

The costs presented are based on taking syngas from the 1361 Mg/d (1,500 TPD) unit used as the base case. Because of the lesser system utilization factor (0.88) resulting from the addition of the ammonia conversion plant, only 438 178 Mg/y (483,000 TPY) of raw refuse would be processed and 104 328 Mg/y (115,000 TPY) of ammonia produced.

Capital Cost

Capital cost for a complete solid waste to ammonia facility would start with the cost of the syngas production facility, to which would have to be added a complete ammonia conversion unit. The ammonia plant could be adjacent to the syngas facility or at some distance away. The connection between the two is a pipeline, whose cost is directly proportional to distance. Land requirement is 32 400 m^2 (8 acres) at a minimum and located such as to incorporate a rail siding since much of the ammonia distribution from the plant would be by railway tank car. Electric power up to 20,000 kVA will be required and a water supply approximately equal to the syngas plant will be needed. The location should be away from populated areas because of the possibility of accidental release of ammonia.

The construction cost is estimated at $31.6 million for the ammonia unit and the total plant construction cost at $85.35 million including the front-end and syngas units. The capital cost for this total plant system are presented in Table C-8 and amounts to $100.66 million in 1975 dollars.

Operating Costs

Operating costs are listed in Table C-9 for the ammonia unit and the syngas plant, including the front-end and gasifier. The same degree of uncertainty applies to these figures as with the capital costs.

TABLE C-8. ESTIMATED CAPITAL COST REQUIREMENTS FOR AMMONIA (1975 DOLLARS)

Item	Cost ($ million)
Construction:	
Front-end processing and syngas plant	53.75
Ammonia conversion plant	31.60
Interest during construction	7.25
Startup costs	4.84
Working capital	3.22
Total	100.66

TABLE C-9. ANNUAL OPERATING COSTS FOR AMMONIA (1975 DOLLARS)

Item	Cost ($000)
Ammonia Unit:	
Labor	404
Power	3,374
Maintenance	1,580
Production Materials	345
Water	178
Subtotal	5,881
Front-End and Purox System	7,016
Plant Total	12,897

In the table, labor includes only operating labor; maintenance labor is included in the Maintenance item. The operating cost shown is equivalent to \$29.42/Mg (\$26.69/ton) of raw refuse or \$123.62/Mg (\$112.15/ton) of ammonia.

ECONOMIC ANALYSIS FOR AMMONIA PLANT

Unit capital amortization cost is \$101.95/Mg (\$92.49/ton) of ammonia. With the operating cost of \$123.62/Mg (\$112.15/ton) ammonia added, the total unit cost is \$225.56/Mg (\$204.63/ton) of ammonia produced, or \$53.82/Mg (\$48.83/ton) raw refuse.

Applying credits due to revenues from drop charges and sale of aluminum and iron, the net cost can be lowered considerably as shown in summary Table C-10. As an example, a drop charge of \$11.02/Mg (\$10/ton) of raw refuse and sale of recovered aluminum at \$331/Mg (\$300/ton) and steel at \$44/Mg (\$40/ton) yields a net cost for producing ammonia of \$158.73/Mg (\$144/ton) ammonia. Marketing and wholesale delivery of ammonia can increase the cost to the manufacturer of ammonia, but was not included; this could be approximately \$28/Mg (\$25/ton) of ammonia.

Ammonia manufacture is more acceptable in regions with a high drop-charge. For this reason, the City of Seattle found it financially feasible to proceed to a preliminary engineering phase with ammonia manufacture because the drop-charge used is about \$13.23/Mg (\$12/ton) raw refuse. Parsons, in a recent study for the Denver Regional Council of Governments (Ref. C-2), found that ammonia manufacture was not financially acceptable because of the low drop-charge available at their landfills. Another method of resource recovery was recommended.

SUMMARY OF ALTERNATIVE USES OF PUROX

In summary, results of all costs associated with the Purox gasification system and the addition of conversion to methane, electric power, methanol, and ammonia are presented in Table C-10. Comparisons can be made, but this may be meaningless unless the products being compared each have a specific market in a given area. It is therefore recommended strongly that a thorough engineering study be made for each community interested in disposing refuse in a useful manner to determine which of several systems and products would fit their needs. In particular, net cost of operation or drop-charge to break even with given markets are items best describing the system rather than construction or capital costs alone.

TABLE C-10. NET COSTS(1) TO PRODUCE PRODUCTS USING SYNGAS

1500-TPD - 7 D/Wk, 1750-TPD - 6D/Wk Delivery, 110-TPH - 16 hrs/D Feed Preparation Rate
Revenues: $40/T Steel, $300/T Aluminum, Drop Charge Listed 0,5,10 $/T
Amortization 8.5%, 20 Years

Product	Product(4) Rate	Capital cost $ million	Annual O&M cost ($000)	$/T Raw refuse(3)			$/Million Btu(3)			$/T Product(3)			mils/kWh(3)		
				Drop charge $/T 0	5	10	Drop charge $/T 0	5	10	Drop charge $/T 0	5	10	Drop charge $/T 0	5	10
Syngas (Fuel Gas)	27.7 x 10^6 SCFD	62.40	7,016	22.56	17.56	12.56	3.30	2.53	1.84	--	--	--	--	--	--
Methane (SNG)	8.2 x 10^6 SCFD	79.93	8,253	31.44	26.44	21.44	6.20	5.22	4.23	--	--	--	--	--	--
Electric Power (2)	25.94 MW	79.96	5,945	24.71	19.71	14.71	--	--	--	--	--	--	60.9	48.6	36.2
Methanol	245 TPD	89.14	11,372	38.68	33.68	28.68	10.94	9.53	8.11	237	206	176	--	--	--
Ammonia	356 TPD	100.66	12,897	44.38	39.38	34.38	--	--	--	186	165	144	--	--	--

(1) In 1975 Dollars the net cost is defined as amortization of capital cost plus operating cost less revenues from steel and aluminum sale, and drop charges.
(2) Net power shown - all power to Front End, Purox System and Gas Compressor furnished by Turbo-Electric Plant.
(3) Alternate unit costs are directly related by ratio of product rate to raw refuse delivery rate of 1,500 TPD.
(4) HHV's of Products: Syngas 370 Btu/SCF, methane (SNG) 927 Btu/SCF, Methanol 21.64 x 10^6 Btu/Ton. The utilization factor on a yearly basis is Syngas 0.92, methane 0.85, electric power 0.91, methanol 0.88, ammonia 0.88.

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C-2. "Resource Recovery from Solid Waste," Vol. II, The Ralph M. Parsons Co., Report for Denver Regional Council of Governments, Denver, 1976.

C-3. White, G. A., T. R. Roszkowski, and D. W. Stanbridge, "The RM Process," in Methanation of Synthesis Gas, American Chemical Society, 1975.

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C-5. Reed, T. B., et al., "Improved Performance of Internal Combustion Engines Using 5 to 30% Methanol in Gasoline," Lincoln Laboratories, MIT, Cambridge, Massachusetts.

C-6. Slack, A. V. and G. R. James, Ammonia, Part 1, Marcel Dekker, N. Y., 1975, p 342.

C-7. Ibid, p 293, 334.

C-8. Ibid, p 338.

APPENDIX D

ENVIRONMENTAL CONTROL CONSIDERATIONS

AIR POLLUTION

Introduction

A brief discussion of air pollution considerations follows that encompasses:

- The problem of air pollution
- Emission standards
- Air pollution control equipment selection factors
- Air pollution control equipment
- Air pollution control equipment costs

More detailed information can be obtained by examination of the associated references and by consulting manufacturers of air pollution control equipment.

The Problem of Air Pollution

Air pollution consists of particulate matter or impurities that are suspended in or conveyed by a moving stream of gas or air. An air pollution problem arises when the concentration of these substances interferes with the public well-being. The Engineers Joint Council has developed a specific definition:

> "Air pollution means the presence in the outdoor atmosphere of one or more contaminants, such as dust, fumes, odor, smoke or vapor, in quantities, or characteristics, and of duration such as to be injurious to human, plant or animal life or to property which unreasonably interfere with the comfortable enjoyment of life and property." (Ref. D-1)

The air pollutant problems usually encountered by energy producing industries include particles, sulfur oxides, nitrogen oxides, and visibility. Of the mentioned pollutant problems, particles generally cause the most concern. Particles can take many forms and are defined in Table D-1.

TABLE D-1. DEFINITIONS OF PARTICLE TYPES (Ref. D-2)

Particulate Matter:	Any material, except uncombined water, in the form of solid or liquid in the atmosphere or in a gas stream.
Aerosol:	Solid or liquid particles of microscopic size, such as smoke, fog or mist.
Dust:	Solid particles larger than colloidal size and capable of suspension in air and other gases.
Flyash:	Particles formed as a result of combustion of fuel.
Fog:	Visible aerosols where liquid is the dispersed phase.
Fume:	Particles formed by condensation, sublimation or chemical reaction, e.g., condensed metal oxides.
Mist:	Low concentration dispersion of relatively small liquid droplets.
Particle:	Small, discrete mass of solid or liquid matter.
Smoke:	Small particles resulting from incomplete combustion of combustible material.
Soot:	An agglomeration of tarry carbon particles formed by incomplete combustion of carbonaceous material.

Sulfur oxides are formed whenever a fuel or fuels containing sulfur or its compounds are burned. The major portion of these emissions is sulfur dioxide (SO_2). Sulfur oxide emission levels vary directly with the amount of sulfur originally in the fuel utilized. Normally high sulfur fuel will generate high sulfur emissions and low sulfur fuel will generate low sulfur emissions, etc.

Nitrogen oxides are formed during usual combustion processes due to reaction of the nitrogen and oxygen in the combustion air supply. Nitric oxide (NO) and nitrogen dioxide (NO_2) formation increases as the temperature of combustion increases.

Visibility is not a pollutant in itself, but is a direct result of various types of particle pollutants. Visibility (or opacity) is categorized as a pollutant due to the fact there is a general correlation between plume opacity and the quantity of pollutants released, thereby providing an inexpensive and simple means of enforcement by visual inspection.

Control of the above described air pollutants can take many forms, but before control can be accomplished a criteria must be established as to what allowable level of pollutant emissions will be maintained. These criteria are called emission standards.

Emission Standards for Air Pollution

Emission standards can be categorized into seven general areas. These seven areas and a brief outline of what they encompass can be found in Table D-2. Some or all of these emission standards may be applicable to a particular point source, the choice being dependent on the controlling agency involved. Consideration of air pollutant emission standards is an essential step when deliberating over modifications, or new plant design of energy generating systems.

TABLE D-2. CATEGORIES OF EMISSION STANDARDS

Standards Category	Coverage
1. Visible emissions	Based on emission plume opacity usually utilizing Ringlemann scale of obscuring power.
2. Particulate matter concentration	Based on either a) weight concentration of particles in stack, or b) relationship between weight of emitted particles to the total weight of material processed.
3. Exhaust gas concentration	Limits gaseous emissions to a prescribed level based either on a ratio of the stack gas on the total weight of material processed.
4. Emission Prohibition	Bans certain types of emissions.
5. Performance standards	Based on either: a) regulation of process operations so as to not exceed maximum emission rate, or b) equipment design standards.
6. Regulation of fuel	Limit types of fuels used in burning.
7. Zoning restrictions	Limits certain of industries from operating in a particular area.

Performance standards for new or modified sources have not been promulgated on the Federal level for many types of waste to energy facilities. If such is the case for a particular facility, a request for determination must be made to the regulating agency. After a review of engineering, design, and equipment data, the source will be categorized under an existing performance standard, or other provisions made. The new or modified facility will then have to meet state and local regulations if these are more restrictive than federal ones. Some selected new source performance standards are shown in Table D-3 that may be applicable to waste to energy facilities.

When the required emission standards have been discerned for the proposed facility, selection of pollution control equipment that will meet the emission standards and also be compatible with facility operations can begin.

Air Pollution Control Equipment Selection Factors

The selection of equipment for air pollution control for a particular application is dependent on many factors, including physical characteristics of the pollutant, carrier gas characteristics, process factors, operational factors, emission standards, and costs. They can be described as follows:

> Physical characteristics include particle size distribution, weight, density, shape, hygroscopicity, agglomerating tendency, corrosiveness, stickiness, flowability, electrical conductivity, flammability, and toxicity.
>
> Carrier gas characteristics include temperature, humidity, viscosity, pressure, corrosiveness, toxicity, electrical conductivity, flammability, and explosiveness.

TABLE D-3. SELECTED NEW SOURCE PERFORMANCE STANDARDS (Ref.D-3)

Pollutant	Fossil Fuel Fired Steam Generator Grains/Million Cal Heat Input	Incinerators Grains/dscm	Sewage Plant Sludge Incinerators (Grains/kg dry sludge input
Particulates	0.18	0.18	0.65
NO_x	1.4# , 2.2*	-	-
SO_2	0.36# , 0.54* , 0.26≠	-	-
Opacity	20%	-	20%

Notes: # Liquid fuel, * Solid fuel, ≠ gaseous fuel.

Process factors include gas flow rate, particle density, collector system efficiency requirements, pressure differential allowed, product quality requirements, process material rate of flow, and quality variations in process material.

Operational factors include available floor space, headroom, construction material limitations due to process factors, power requirements, temperature limitations, pressure drops, maintenance problems, and waste disposal.

Emission standards are discussed in the subsection entitled "Emission Standards for Air Pollution."

Costs include purchase, installation, operation, and maintenance of air pollution control equipment. Costs are further discussed in the subsection entitled "Air Pollution Control Equipment Costs."

Selection of air pollution control equipment must be made with consideration of changing emission standards and the rapidly changing control technology. The year data is compiled is very significant since equipment, material, and labor costs have risen each year.

In selecting air pollution control equipment, collection efficiency is a major deciding factor. Collection efficiencies for various air pollution control devices are shown in Table D-4, where it can be seen that there is a wide range of efficiencies. These efficiencies depend on the selection factors previously discussed that lead to system compatibility of the control equipment. An understanding of the different air pollution control devices and how they operate is needed before deciding on a piece of equipment that will be compatible with the proposed facility.

Air Pollution Control Equipment

Air pollution control devices are typically designed either to remove particles or gaseous effluents and are traditionally grouped according to the means used to remove the undesirable components from an effluent stream. These devices can be categorized into six distinct classes:

- Mechanical Collectors
- Filters
- Wet Scrubbers
- Electrostatic Precipitators
- Combusters or Afterburners
- Stacks.

TABLE D-4. AIR POLLUTION CONTROL EQUIPMENT COLLECTION EFFICIENCIES (Ref.D-4)

Equipment Type	Typical efficiency ranges (on a total weight basis) (%)
Electrostatic precipitator[a]	80 to 99.5$^+$
Fabric filters[b]	95 to 99.9
Mechanical collector	50 to 95
Wet collector	75 to 99$^+$
Afterburner	
Catalytic[c]	50 to 80
Direct flame	95 to 99

a Most electrostatic precipitators sold today are designed for 98 to 99.5% collection efficiency.

b Fabric filter collection efficiency is normally greater than 99.5%.

c Not normally applied in particulate control; has limited use because most particulate matter poisons or desensitizes the catalyst.

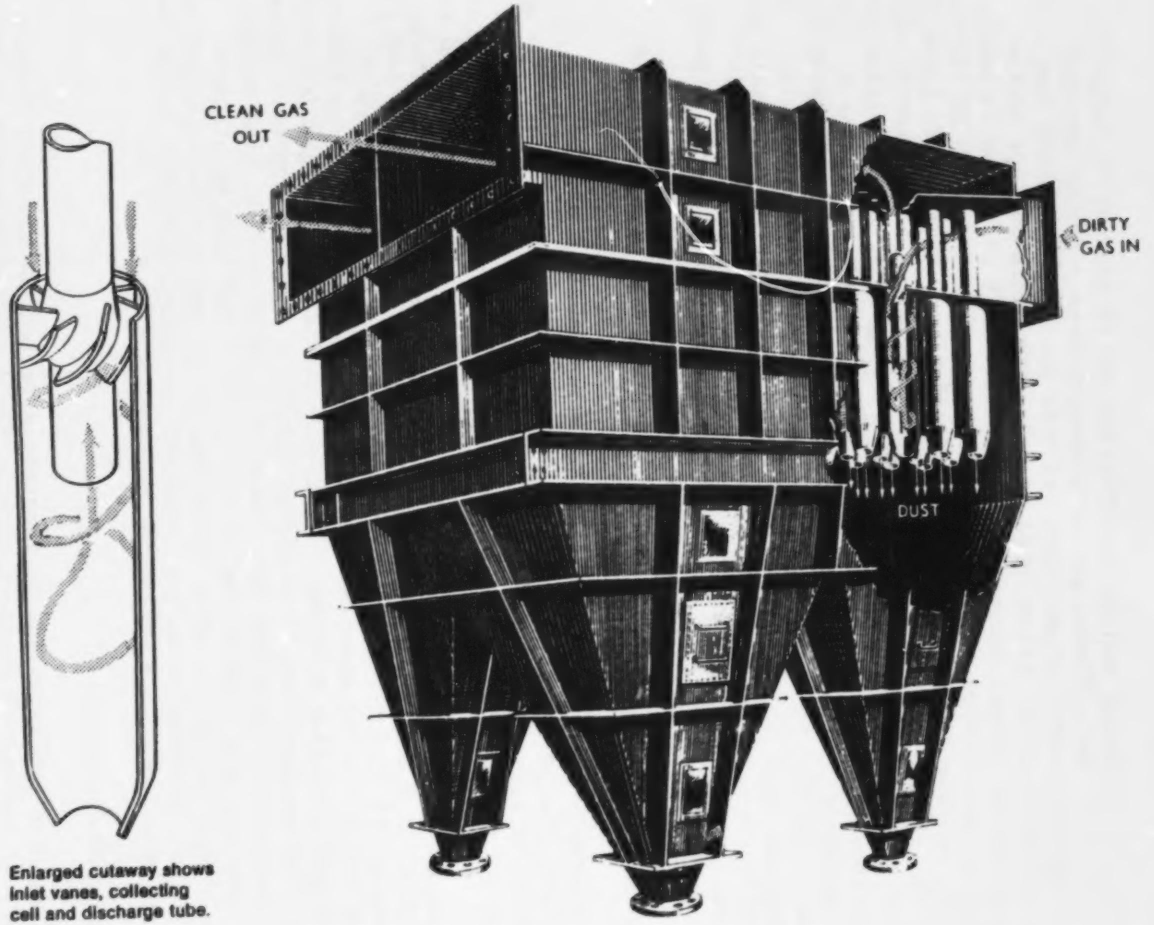
Mechanical Collectors--

Mechanical collectors (See Figure D-1) are specifically used for the removal of particle emissions and are considered the simplest method of particle control. Removal is effected by either gravity, particle inertia, or centrifugal force.

Settling chambers slow the effluent gas flow allowing gas particles to fall out due to gravity.

Inertial separators collect particles on stationary impaction targets and are the most widely used type of pollution control equipment.

Cyclones are a specific type of inertial separator that swirl the effluent gas stream inside its cylindrical shape, thereby forcing the high density particles to the sidewalls by centrifugal means and are separated from the effluent gas stream when they fall to the bottom of the cyclone. Efficiencies depend mainly upon particle characteristics with removal efficiency decreasing rapidly with decreasing particle size. These units are most effective in collecting particles 15 micrometers or larger. Efficiencies vary widely and range from 20% to 90%. The chief advantages of mechanical collectors are the


CLEAN GAS OUT
DIRTY GAS IN
DUST

Enlarged cutaway shows inlet vanes, collecting cell and discharge tube.

Figure D-1. Typical cyclonic dust collector.

low purchase and operating costs, with the major deficiencies being low efficiency and large space requirements. In most cases, mechanical collectors are used as first stages in more complex air pollution control systems. The particulate matter after collection is usually disposed in landfills.

Filters--

Mechanical screening can be an effective way to trap solid particles. In this type of unit, the effluent gas is passed through a porous material (a filter or baghouse installation) that collects particulate matter larger than the pore (or mesh) size.* Fibers used as filtering media include cotton, Dynel, wool, nylon, Orlon, Dacron, and glass, all with variation in weave, count, finish, etc. Other variations include the size and shape of filters, arrangement, spacing of bags, and method of cleaning. Systems are generally efficient for the collection of particles greater than 0.5 micrometer, with efficiencies over 99% a common occurrence. In operation, the particles are initially captured and retained on the fibers of the cloth by means of interception, impingment, diffusion, gravitational settling, and electrostatic attraction, with the cloth periodically cleaned of entrapped particles. The chief advantages of a filtering system are high efficiencies with small and large particles and moderate pressure drop. The disadvantages are 290°C (550°F) temperature limit, costly bag replacement, and unit size. Figures D-2 and D-3 show typical systems.

Wet Scrubbers--

Wet scrubbers use the action of a liquid colliding with the pollutant to remove solids, liquids, and gases from effluent streams (See Figures D-4 and D-5). Collision causes the pollutant to be absorbed by the wet scrubbing medium and the resulting sludge or solution is then physically removed from the system. The units are effective at moderately high temperatures and are not significantly affected by particle loading. Wet scrubbers are increasingly utilized as a method of air pollution control, with efficiency varying between 80% and 99.5% for particles ranging from less than 1μm to 10 μm. Disposal of the collected material in water without clarification or treatment may cause water pollution problems. Scrubbers are usually categorized as low energy and high energy types. Low energy scrubbers have low capital, operation, and maintenance costs and also lower efficiency, whereas high energy scrubbers have moderate capital and operation costs and high maintenance costs, but high efficiency. Other disadvantages of wet scrubbers include corrosion problems, freezing in cold weather, water vapor visibility during certain weather conditions, and contamination of exhaust gas.

Electrostatic Precipitators--

Electrostatic precipitation is frequently called the Cottrell process and consists of the use of an electrostatic field for precipitating or removing solid or liquid particles from a gas in which particles are carried in suspension (See Figures D-6 and D-7). The basic principles involved are

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*Once a filter cake has built up on the surface, much smaller particles can be retained.

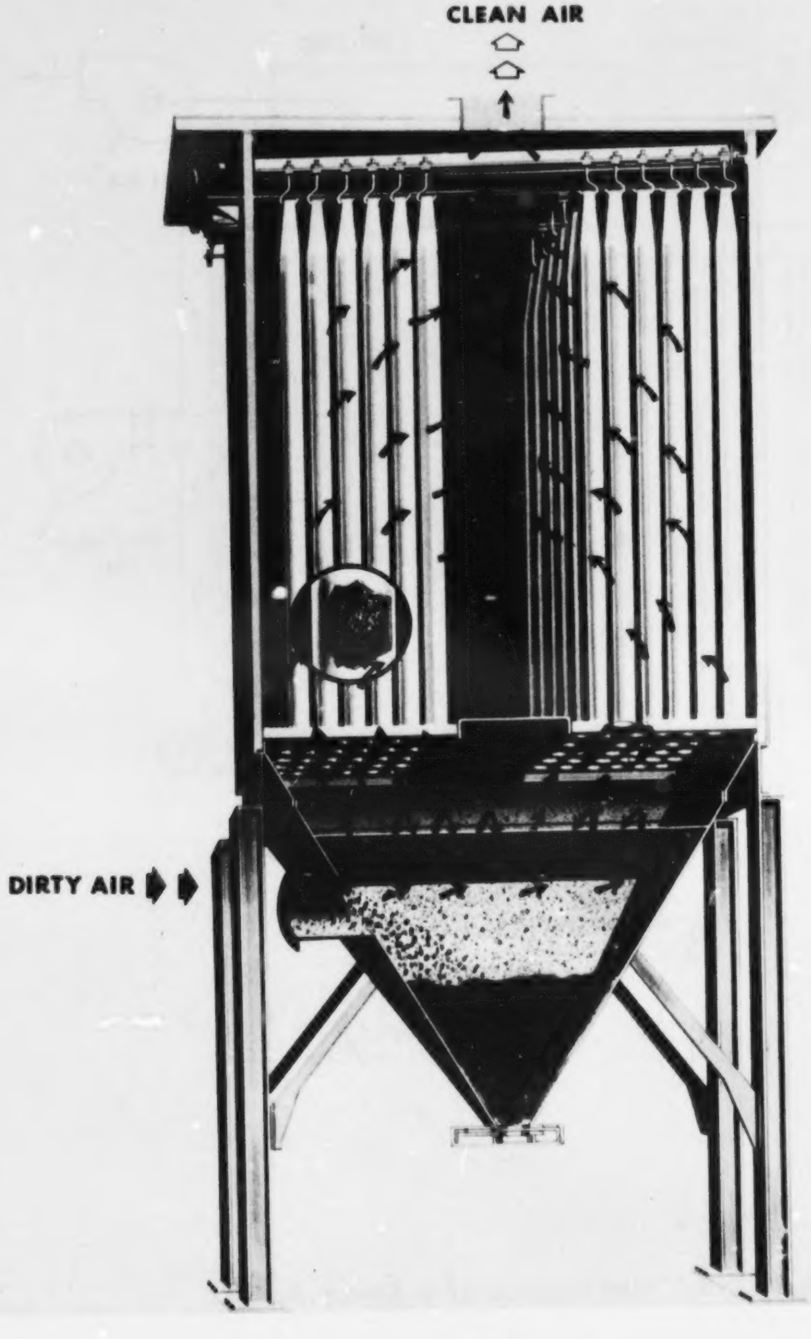
CLEAN AIR
DIRTY AIR

Figure D-2. Shaker-type fabric filter.

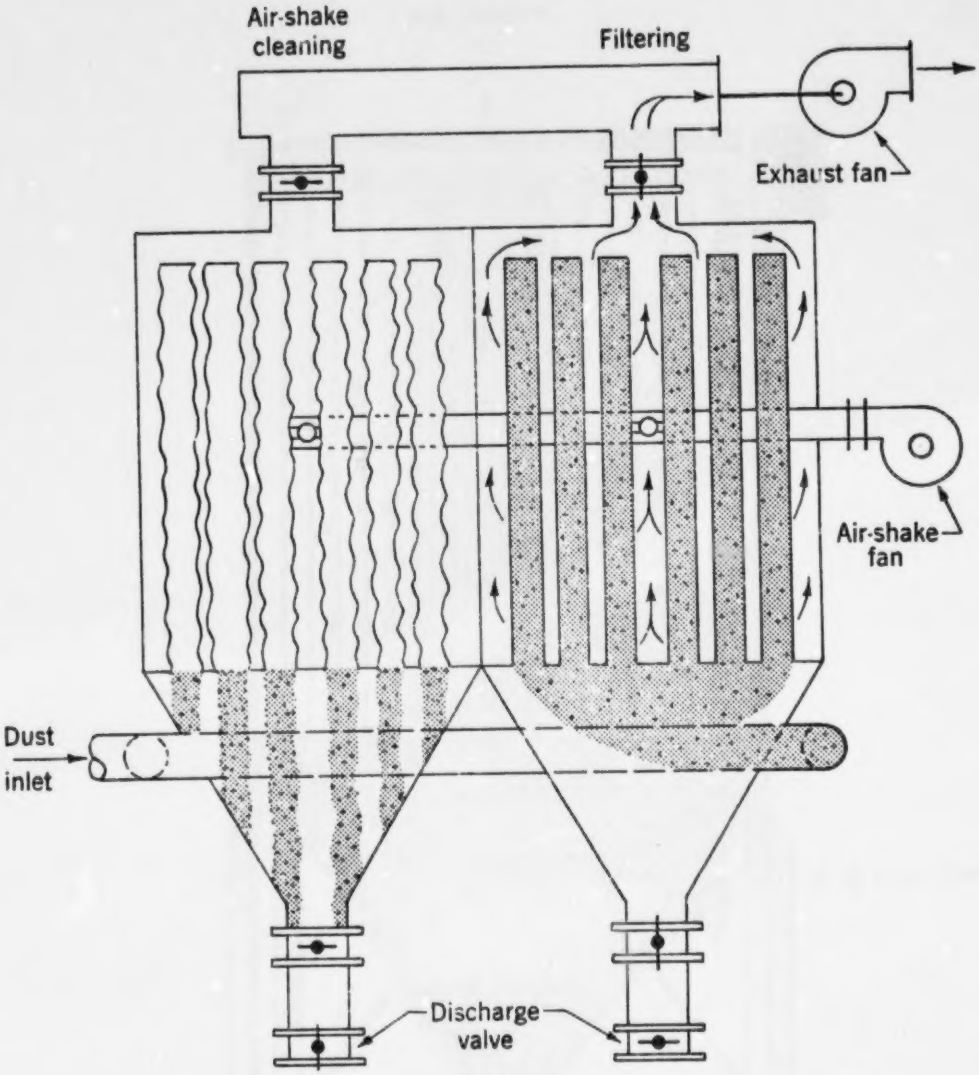
Air-shake cleaning
Filtering
Exhaust fan
Air-shake fan
Dust inlet
Discharge valve

Figure D-3. Flow diagram of a fabric filter.

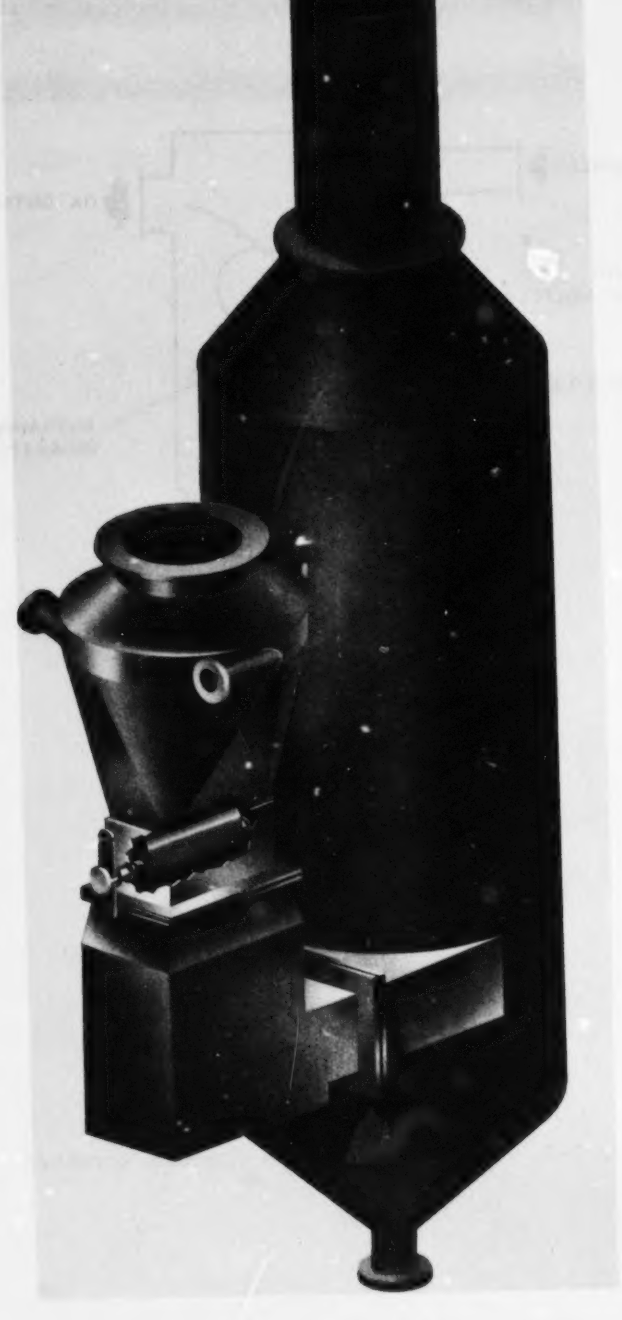

Figure D-4. Flooded wall Venturi scrubber.

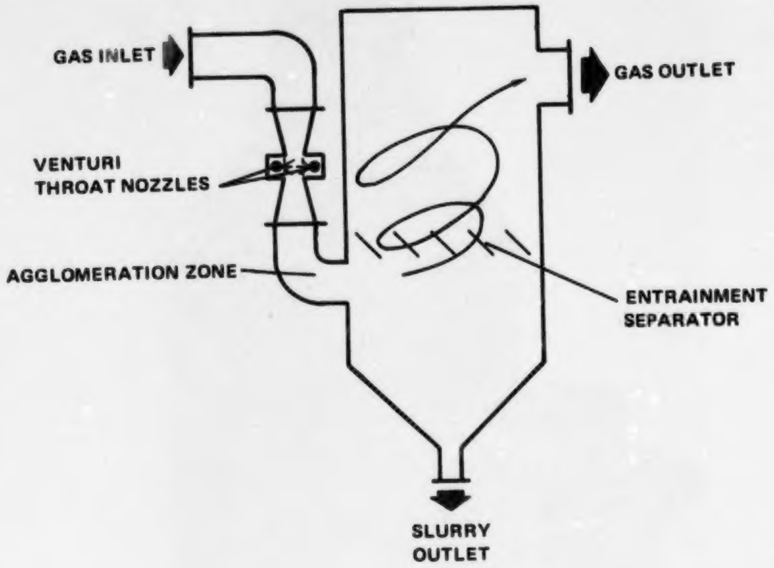
GAS INLET
GAS OUTLET
VENTURI THROAT NOZZLES
AGGLOMERATION ZONE
ENTRAINMENT SEPARATOR
SLURRY OUTLET

Figure D-5. Flow diagram of a Venturi scrubber.

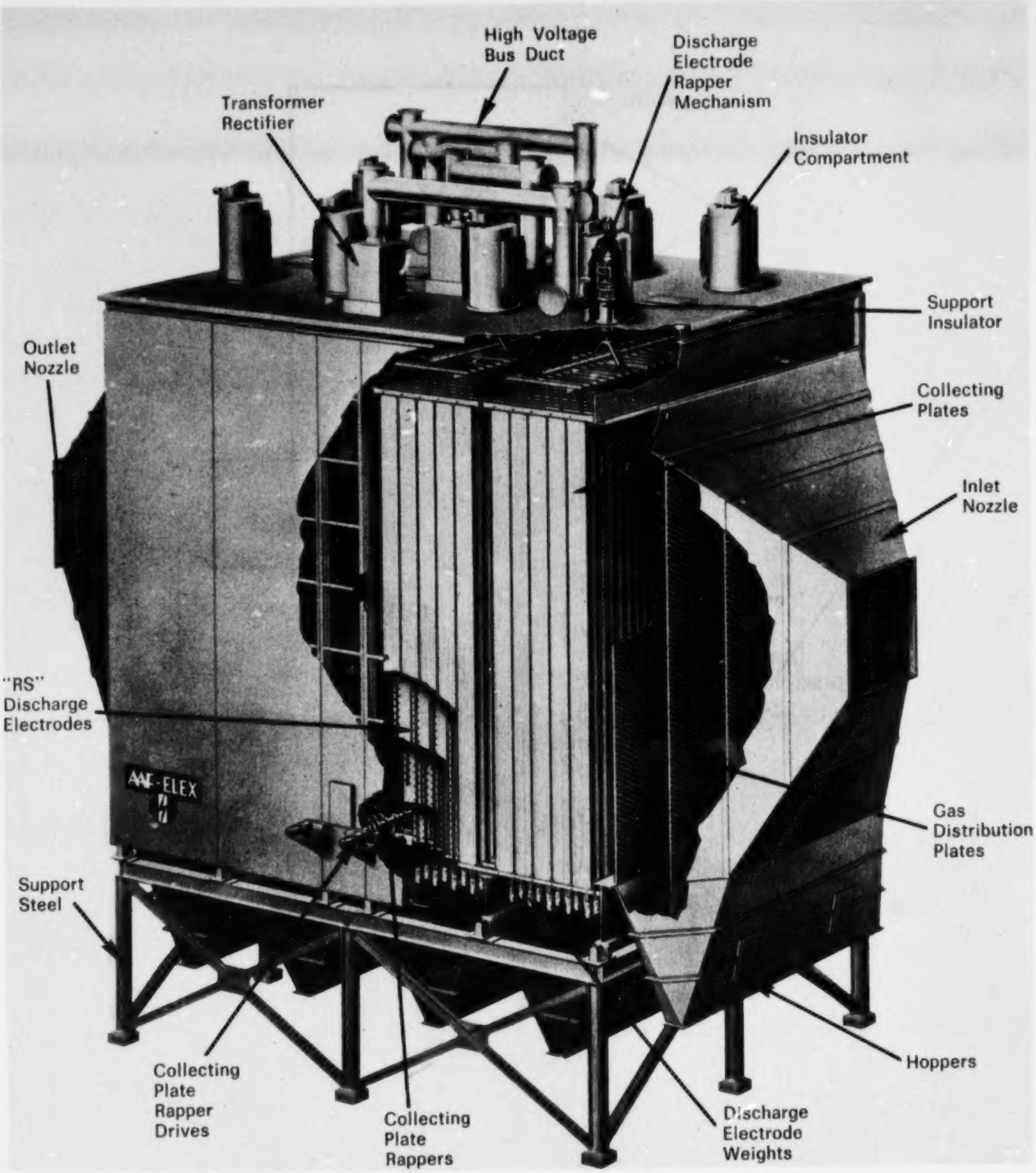
High Voltage Bus Duct
Discharge Electrode Rapper Mechanism
Transformer Rectifier
Insulator Compartment
Support Insulator
Outlet Nozzle
Collecting Plates
Inlet Nozzle
"RS" Discharge Electrodes
AAF-ELEX
Gas Distribution Plates
Support Steel
Hoppers
Collecting Plate Rapper Drives
Collecting Plate Rappers
Discharge Electrode Weights

Figure D-6. Cut-away view of an electrostatic precipitator.

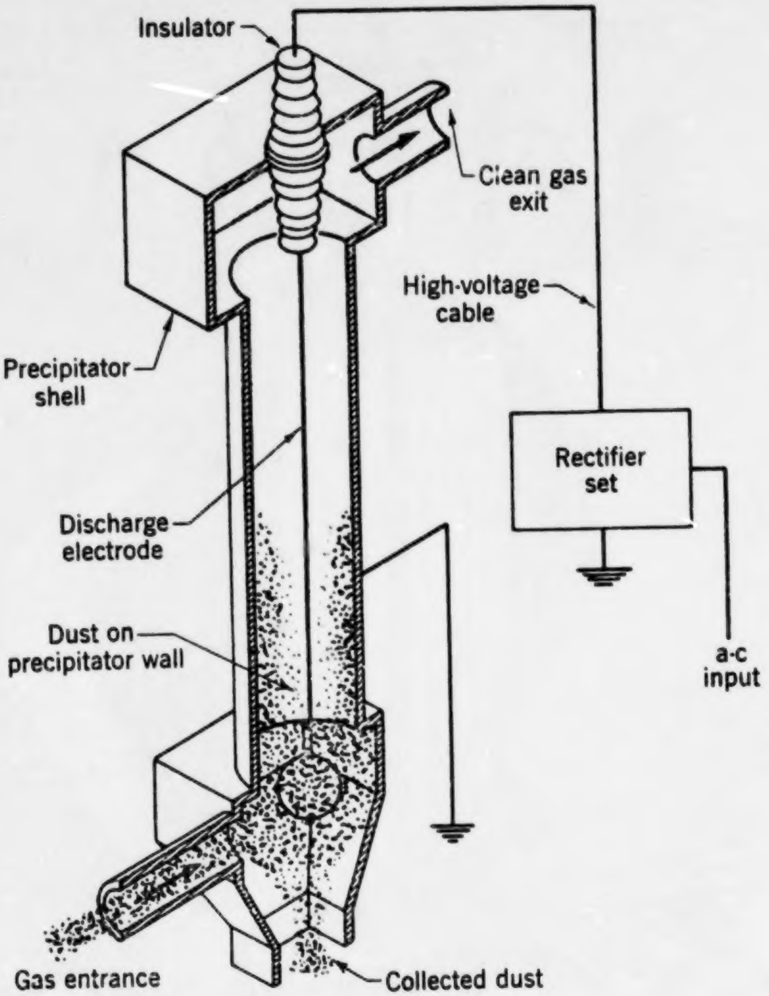
Insulator
Clean gas exit
High-voltage cable
Precipitator shell
Rectifier set
Discharge electrode
Dust on precipitator wall
a-c input
Gas entrance
Collected dust

Figure D-7. Flow diagram showing elements of an electrostatic precipitator.

particle ionization, normally by a discharge electrode, and then entrapment by a collecting plate, normally consisting of a grounded electrode. Electrostatic precipitators effectively collect a wide range of particle sizes from 1 to 100μm range. Efficiencies in excess of 99.5% can be achieved in many cases. A mechanical collector generally precedes an electrostatic precipitator because large particles can cause damage to the discharge electrodes. Particles collected are usually disposed in landfills. Precipitators are divided into two general types: 1) single-stage (Cottrell) and 2) two-stage (Penney), with both operating on essentially the same principles. The differences in the single-stage and two-stage basically arise in the manner of particle ionization and the use of high and low voltage, respectively. The single-stage is also designed for use in processing large volumes of air. The advantages of an electrostatic precipitator are its high efficiency and relatively low operating costs, with the disadvantages being high capital cost, critical electrode voltage requirements, the constant cleaning necessary, and use of a precleaner, generally a cyclone, for the gas effluent.

Combustors or Afterburners--

Combustors or afterburners are essentially incineration chambers in which objectional aerosols or gases from some process are oxidized to a less offensive form, ideally to carbon dioxide (CO_2) and water. Supplemental heat, usually required to sustain the oxidation reactions, is supplied by burning auxiliary fuel in either a preheat chamber or in the reaction chamber itself, or by passing the incoming pollutant stream through a heat exchanger. Well designed afterburners, correctly applied and properly maintained, can achieve over 98% destruction of pollutants. Afterburners can be direct-fired or catalytic. Direct-fired (or thermal) afterburners are generally refractory-lined steel enclosures, cylindrical or rectangular in shape, in which the pollutant stream is mingled with the hot gases of a gas or oil burner elevating the pollutant stream temperature till oxidation is complete. A catalytic afterburner operates on the principal fact that many chemical reactions will proceed to completion at well below normally required temperatures in the presence of a catalyst.

Stacks and Chimneys--

Historically, a stack's function was to provide natural draft for combustion. Today, stacks are also used as a means of air pollution control by reducing exhaust gas temperatures and increasing dispersion of contaminants to achieve lower ground level concentrations. Stacks are not a solution to the air pollution problem because they do not reduce the amount of pollutant released to the atmosphere. Limitations on stack emissions to prevent remote pollution problems and atmospheric and ground-level concentration buildup will require the use of other methods of air pollution control. Stack operation is significantly affected by temperature inversions, meteorological conditions, and adjacent buildings and terrain, which are all difficult to predict. Stacks today range up to 300m so as to reach above the inversion layer and provide better dispersion.

Reinforced concrete chimneys are strong and can withstand higher winds than other types. The major disadvantage is that the surface may crack due to temperature and plastic stress conditions. Large chimneys are more economical when they are constructed with concrete rather than other building materials. Masonry chimneys may be constructed from straight or radial bricks or blocks. They are built with a lining shell of fireclay brick that will resist temperatures of 500°C (950°F) and an outer shell of ordinary brick. An annular airspace of 5 to 15 cm (2 to 6 in.) normally separates the two shells. Linings are also used in concrete chimneys. Vibration damage near top can be caused by high exit velocities. Steel chimneys have low initial cost, are easily constructed and are lightweight in comparison to other designs. Disadvantages are high maintenance costs and unsightly appearance. It is more economical to support steel chimneys by guy-wires than to make them self-supporting. A thin lining of bonded fused-glass is normally used on the inside of the steel stack. (Ref.D-2).

Table D-5 shows the various types of collectors mentioned and their collection range of particles. Table D-6 summarizes the approximate characteristics of air pollution control equipment and Table D-7 summarizes the advantages and disadvantages of different air pollution control devices.

When an understanding of air pollution control equipment selection operating factors is achieved, cost comparisons can begin. Air pollution control equipment costs are discussed in a separate subsection.

Air Pollution Control Equipment Costs

Air pollution control equipment costs can be separated into two main categories: capital investment or first cost and operating or repeated costs. Capital cost is the total installed cost of a particular air pollution control

TABLE D-5. TYPES OF COLLECTORS FOR RANGE OF PARTICLE SIZE (Ref.D-5)

Type	Useful Size Range, micrometers
Packed Tower	0.001 to 0.5
High Energy Scrubber	0.03 to 5.0
Low Energy Scrubber	0.001 to 0.008 (gas), 1.0 to 15
Dry Cyclone Collector	8 to 1000
Electrostatic Precipitator	0.008 to 30
Cloth Collector	0.008 to 1000

TABLE D-6. APPROXIMATE CHARACTERISTICS OF DUST AND MIST COLLECTION EQUIPMENT

Equipment Type	Relative Cost[a]	Smallest Particle Collected (μ)[b]	Space	Pressure Drop (Inches H_2O)	Power Used[c] kW / 1000 ft³/min	Max. Temp., °C, Standard Construction	Remarks
A. Settling Chamber			Moderate			400°	
1. Simple	1	40		0.1-0.5	0.1		Large, low pressure drop, precleaner
2. Multiple Tray	2-6	10		0.1-0.5	0.1		Difficult to clean, warpage problem
B. Inertial Separators			Moderate			400°	
1. Baffle Chamber	1	20		0.5-1.5	0.1-0.5		Power plants, rotary kilns, acid mists
2. Orifice Impaction	1-3	2		1.3	0.2-0.6		Acid mists
3. Louver Type	1-3	10		0.3-1	0.1-0.2		Fly ash, abrasion problem
4. Gas Reversal	1	40		0.1-0.4	0.1		Precleaner
5. Rotating Impeller	2-6	5		---	0.5-2		Compact
C. Cyclones						400°	
1. Single	1-2	15	Small	0.5-3	0.1-0.6		Simple, inexpensive, most widely used
2. Multiple	3-6	5	Large	2-10	0.5-2		Abrasion and plugging problems
D. Filters			Large			400°d	
1. Tubular	3-20	0.1		2-6	0.5-1.5		High efficiency, temperature and humidity limits
2. Reverse Jet	7-12	0.1	Moderate	2-6	0.7-1.5		More compact, constant flow
3. Envelope	3-20	0.1		2-6	0.5-1.5		Limited capacity, constant flow possible
E. Electrical Precipitators			Large			650°	
1. One-Stage	6-30	0.1		0.1-0.5	0.2-0.6		High efficiency, heavy duty, expensive
2. Two-Stage	2-6	0.1		0.1-0.3	0.2-0.4		Compact, airconditioning service
F. Scrubbers						Unlimited°	
1. Spray Tower	1-1	10	Moderate	0.1-0.5	0.1-0.2		Common, low water use
2. Jet	4-10	2	---	---	2-10		Pressure gain, high velocity liquid jet
3. Venturi	4-12	1	Moderate	10-15	2-10		High velocity gas stream
4. Cyclonic	3-10	5	Moderate	2-8	0.6-2		Modified dry collector
5. Inertial	4-10	2	Small	2-15	0.8-8		Abrasion problem
6. Packed	3-6	5	Large	0.5-10	0.6-2		Channeling problem
7. Rotating Impeller	4-12	2	Small	---	2-10		Abrasion problem

(Refs. D-6, D-7)

Notes: a- Including necessary auxiliaries. b- With 90-95% efficiency by weight. c- Includes pressure loss, water pumping, electrical energy. d- Glass 400°C, cotton fabric 85°C, synthetic fabrics up to 135°C, Nomex 220°C. e- Precooling of high temperature gases will be necessary to prevent rapid evaporation of fine droplets.

TABLE D-7. ADVANTAGES AND DISADVANTAGES OF COLLECTION DEVICES

Collector	Advantages	Disadvantages
Gravitational	Low pressure loss, simplicity of design and maintenance	Much space required. Low collection efficiency.
Cyclone	Simplicity of design and maintenance.	Much head room required.
	Little floor space required.	Low collection efficiency of small particles.
	Dry continuous disposal of collected dusts.	Sensitive to variable dust loadings and flow rates.
	Low to moderate pressure loss.	
	Handles large particles.	
	Handles high dust loadings.	
	Temperature independent.	
Wet collectors	Simultaneous gas absorption and particle removal.	Corrosion, erosion problems. Added cost of wastewater treatment and reclamation.
	Ability to cool and clean high-temperature, moisture-laden gases.	Low efficiency on submicron particles.
	Corrosive gases and mists can be recovered and neutralized.	Contamination of effluent stream by liquid entrainment.
	Reduced dust explosion risk.	Freezing problems in cold weather.
	Efficiency can be varied.	Reduction in buoyancy and plume rise.
		Water vapor contributes to visible plume under some atmospheric conditions.
Electrostatic precipitator	99+ percent efficiency obtainable.	Relatively high initial cost.
	Very small particles can be collected.	Precipitators are sensitive to variable dust loadings or flow rates.
	Particles may be collected wet or dry.	Resistivity causes some material to be economically uncollectable.
	Pressure drops and power requirements are small compared to other high-efficiency collectors.	Precautions are required to safeguard personnel from high voltage.
	Maintenance is nominal unless corrosive or adhesive materials are handled.	Collection efficiencies can deteriorate gradually and imperceptibly.

TABLE D-7. ADVANTAGES AND DISADVANTAGES OF COLLECTION DEVICES (Continued)

Collector	Advantages	Disadvantages
Electrostatic precipitator (Continued)	Few moving parts. Can be operated at high temperatures (550° to 850°F.)	
Fabric filtration	Dry collection possible. Decrease of performance is noticeable. Collection of small particles possible. High efficiencies possible.	Sensitivity to filtering velocity. High-temperature gases must be cooled to 200° to 550°F. Affected by relative humidity (condensation). Susceptibility of fabric to chemical attack.
Afterburner, direct flame.	High removal efficiency of submicron odor-causing particulate matter. Simultaneous disposal of combustible gaseous and particulate matter. Direct disposal of nontoxic gases and wastes to the atmosphere after combustion. Possible heat recovery. Relatively small space requirement. Simple construction. Low maintenance.	High operational cost. Fire hazard. Removes only combustibles.
Afterburner, catalytic.	Same as direct flame afterburner. Compared to direct flame: reduced fuel requirements, reduced temperature, insulation requirements, and fire hazard.	High initial cost. Catalysts subject to poisoning. Catalysts require reactivation.

(Ref. D-8)

facility and operating costs are those required to run the facility and replace worn out equipment. These costs are a function of many direct and indirect variables as discussed in a separate subsection. For a specific air pollution source, an analysis should include evaluation of all these variables.

In this report, four types of cost curves were developed as a comparison of various types of air pollution control equipment:

- Purchase cost
- Installed cost
- Annual operating cost
- Total annualized costs

These cost curves represent the average or typical situation costs that are generally encountered and should only be utilized as guides for estimating. Development of the cost curves was accomplished by a survey of existing literature and data, updating cost figures found to 1976, and cross checking with known data points. For a particular case, an engineering study of the actual emission source should be made, thereby generating data by which a manufacturer of air pollution control equipment can quote purchase and installed costs and perhaps give a rough estimate of operating costs. It should be kept in mind that the volume of gas to be cleaned is probably the single most important factor in determining the cost of an air pollution control device. System design and process control are other important factors to be considered. Table D-8 illustrates some conditions which could affect purchase and installation costs.

Capital costs can usually be split 50/50 between equipment purchase costs and installation costs. The components of capital cost shown as an average percent of the capital investment is shown in Table D-9.

An additional 15 - 20% of total capital costs represent the cost of startup, working capital, capitalized interest, etc.

Purchase cost curves for various type collectors are shown in Figures D-8 through D-12. Purchase costs are the amounts charged by the manufacturer for equipment of standard construction materials. Special fabrication of equipment to accommodate the particular characteristics of the gas stream can increase the cost dramatically.

Installed costs (Figures D-13 through D-18) include the purchase cost, with additional costs being incurred by 1) erection, 2) insulation, 3) freight costs, 4) site preparation, 5) treatment systems (for wet scrubbers) and 6) auxiliary equipment (fans, duct work, motors, control instrumentation, etc). The installation costs have been assumed to follow those percentages of purchase costs shown in Table D-10.

TABLE D-8. CONDITIONS AFFECTING PURCHASE AND INSTALLATION COSTS

Cost Category	Low to Typical Costs	High to Extreme High Costs
Equipment transportation	Minimum distance; simple loading and unloading procedures	Extensive distance; complex procedure for loading and unloading
Plant age	Hardware designed into new plant as an integral part of process	Hardware installed into confines of old plant requiring structural or process modification or alteration
Available space	Vacant area for location of control system	Little vacant space; extensive steel support construction and site preparation required
Instrumentation	Little required	Complex instrumentation required to assure reliability of control or constant monitoring of gas stream
Guarantee on performance	None required	Guaranteed high collector efficiency to meet stringent control requirements
Degree of assembly	Control hardware shipped completely assembled	Control hardware to be assembled and erected in the field
Degree of engineering design	Standard "package type" control system	Control system requiring extensive integration with process, insulation to correct temperature and moisture problem, noise abatement
Utilities	Electricity, water, waste disposal facilities readily available	Electrical and waste treatment facilities must be expanded; water supply must be developed or expanded
Collected waste material handling	No special treatment facilities or handling required	Special treatment facilities and/or handling required
Labor	Low wages in geographical area	Overtime and/or high-wage geographical area
Auxiliary equipment	Simple draft fan; minimal ductwork	Extensive cooling equipment; ductwork; large motors
Corrosiveness	Noncorrosive gas	Acidic emissions requiring high alloy accessory equipment using special handling and construction techniques
Complexity of start-up	Simple start-up, no extensive adjustment required.	Requires extensive adjustments; testing; considerable downtime.

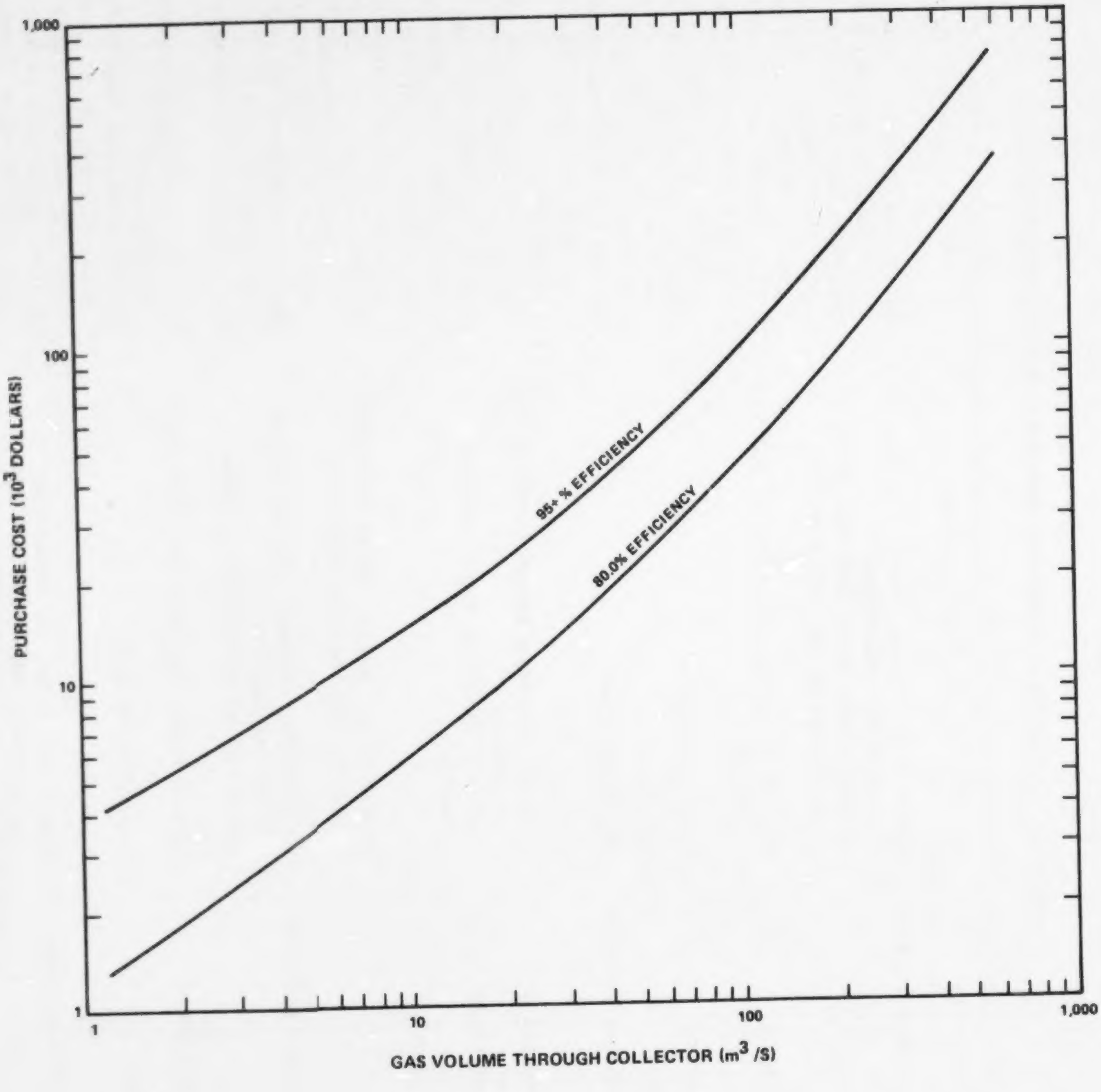

Figure D-8. Estimated purchase cost of mechanical collectors (1976 dollars).

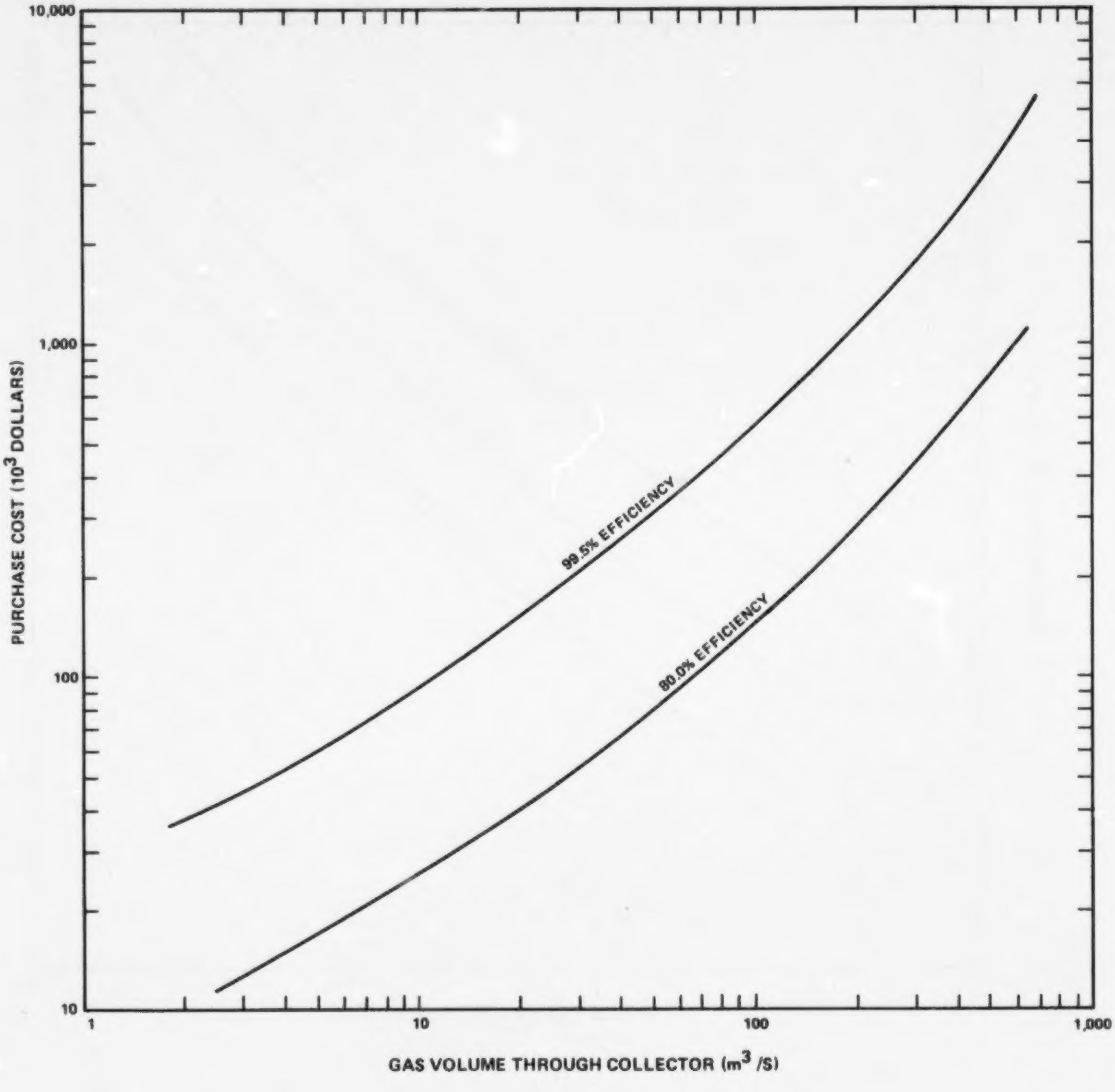

Figure D-9. Estimated purchase cost of wet scrubbers (1976 dollars).

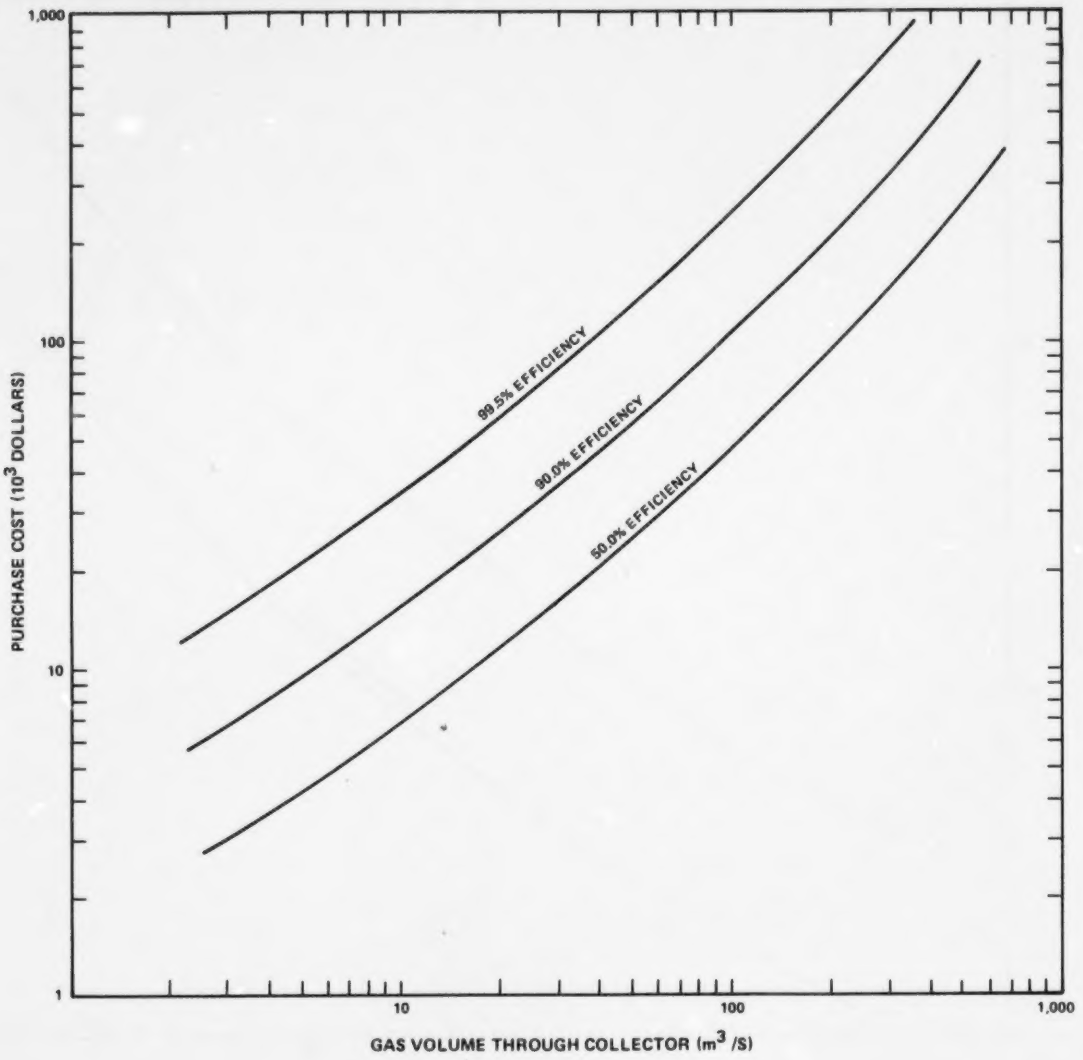

Figure D-10. Estimated purchase cost of fabric filters (1976 dollars).

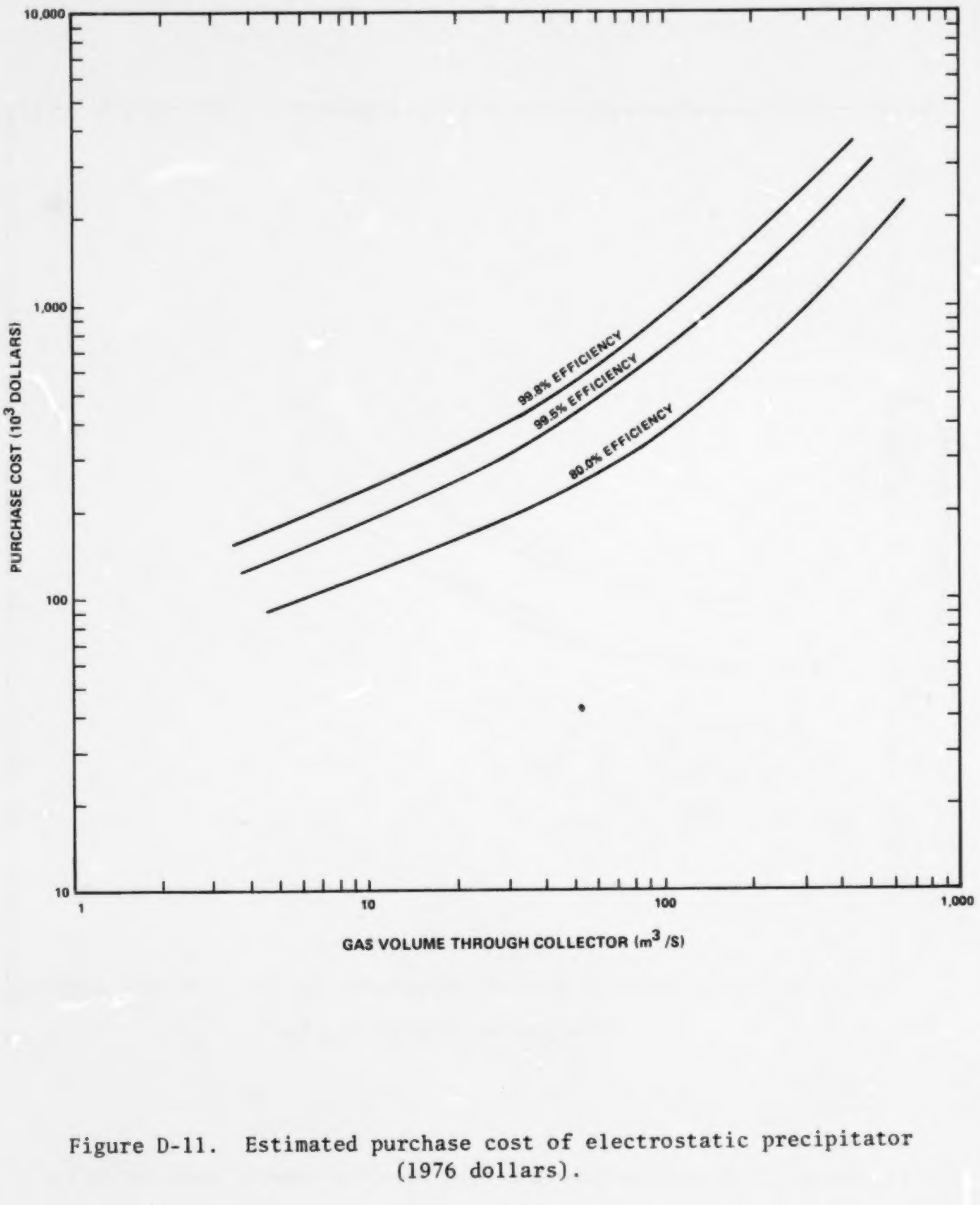

Figure D-11. Estimated purchase cost of electrostatic precipitator (1976 dollars).

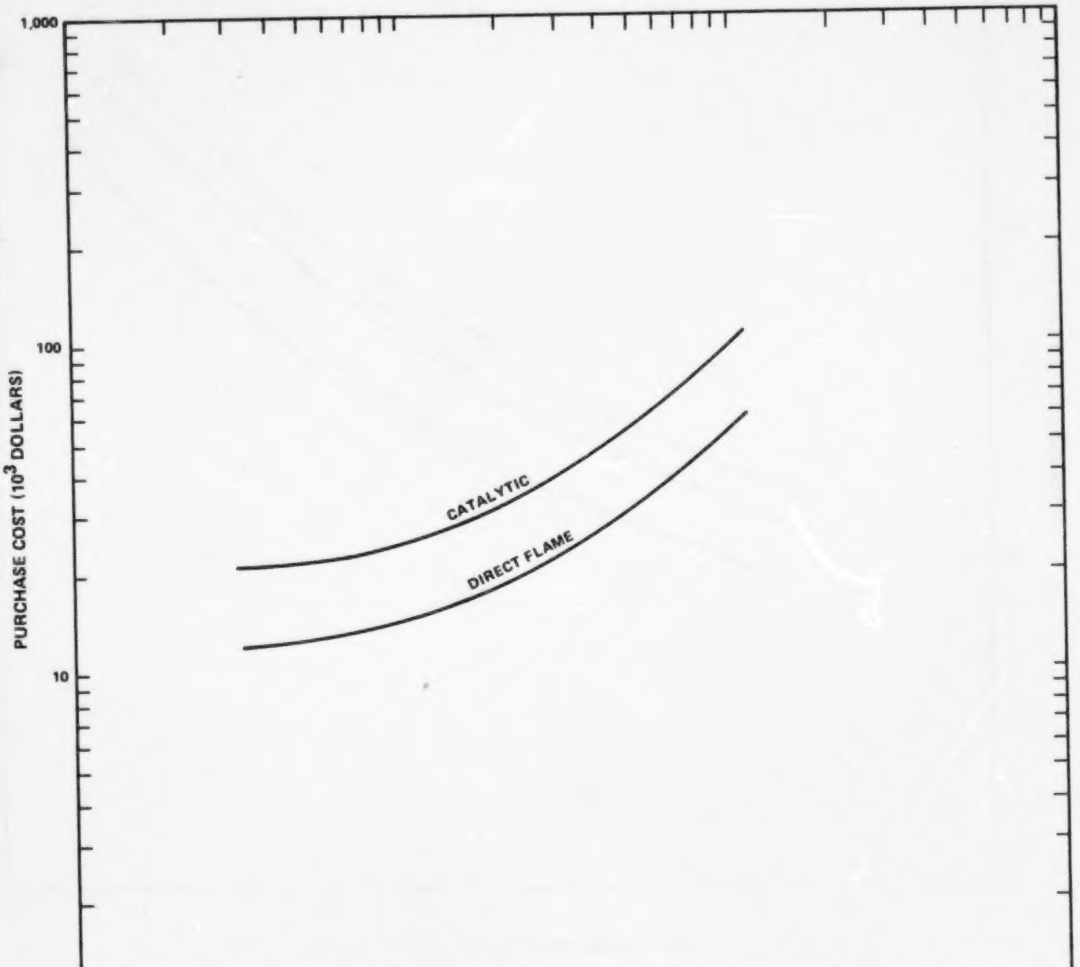

Figure D-12. Estimated purchase cost of afterburners (1976 dollars).

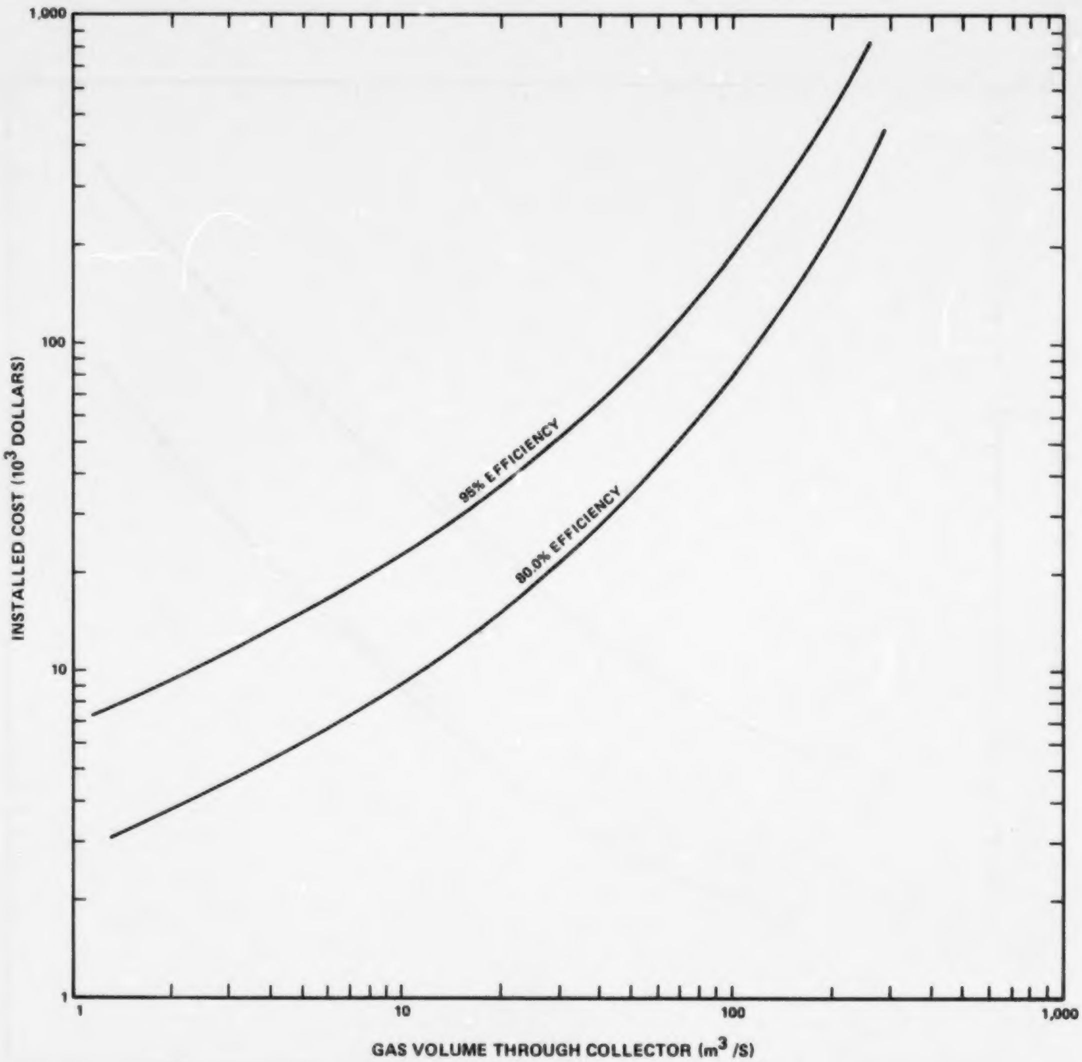

Figure D-13. Estimated installed cost of mechanical collectors (1976 dollars).

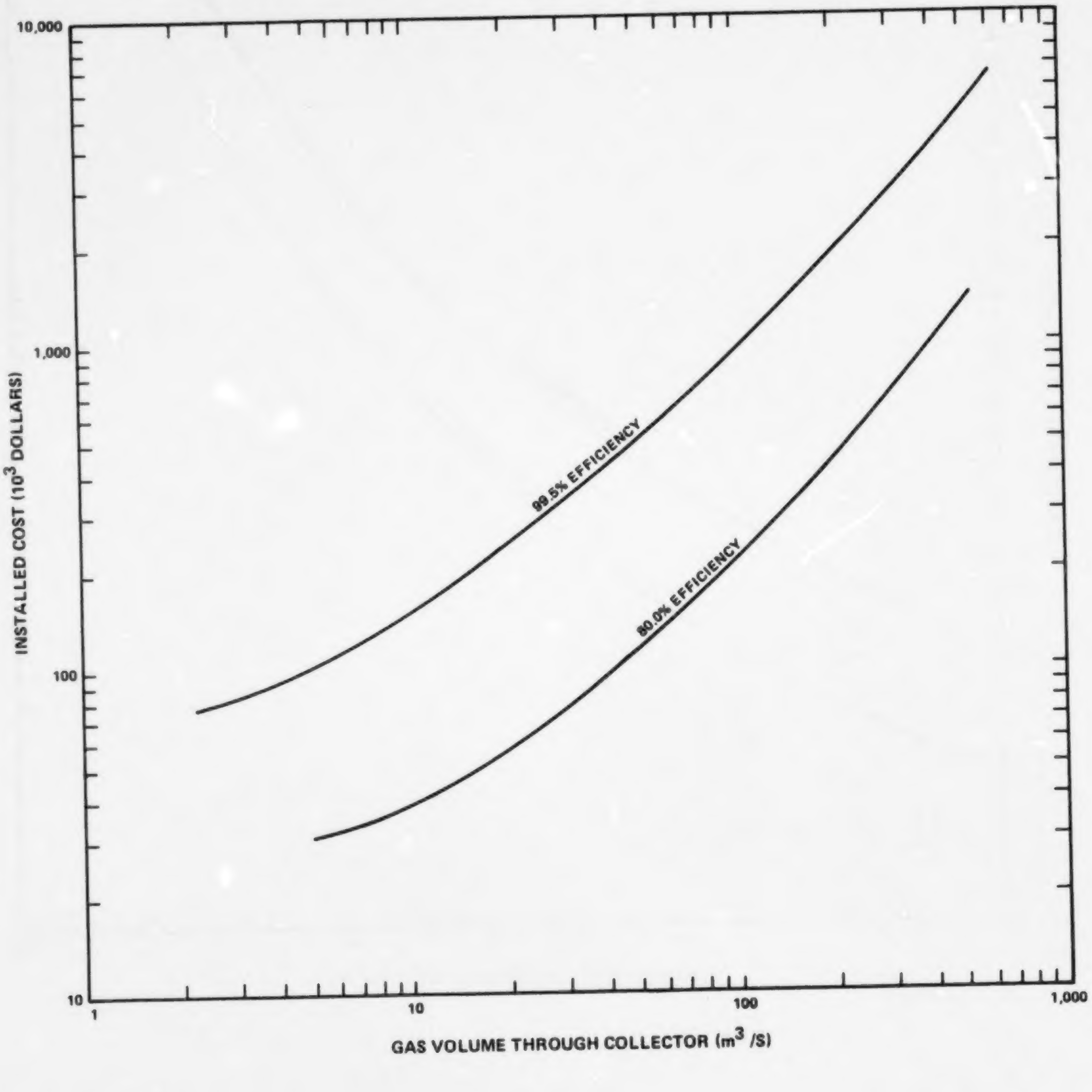

Figure D-14. Estimated installed cost of wet scrubbers (1976 dollars).

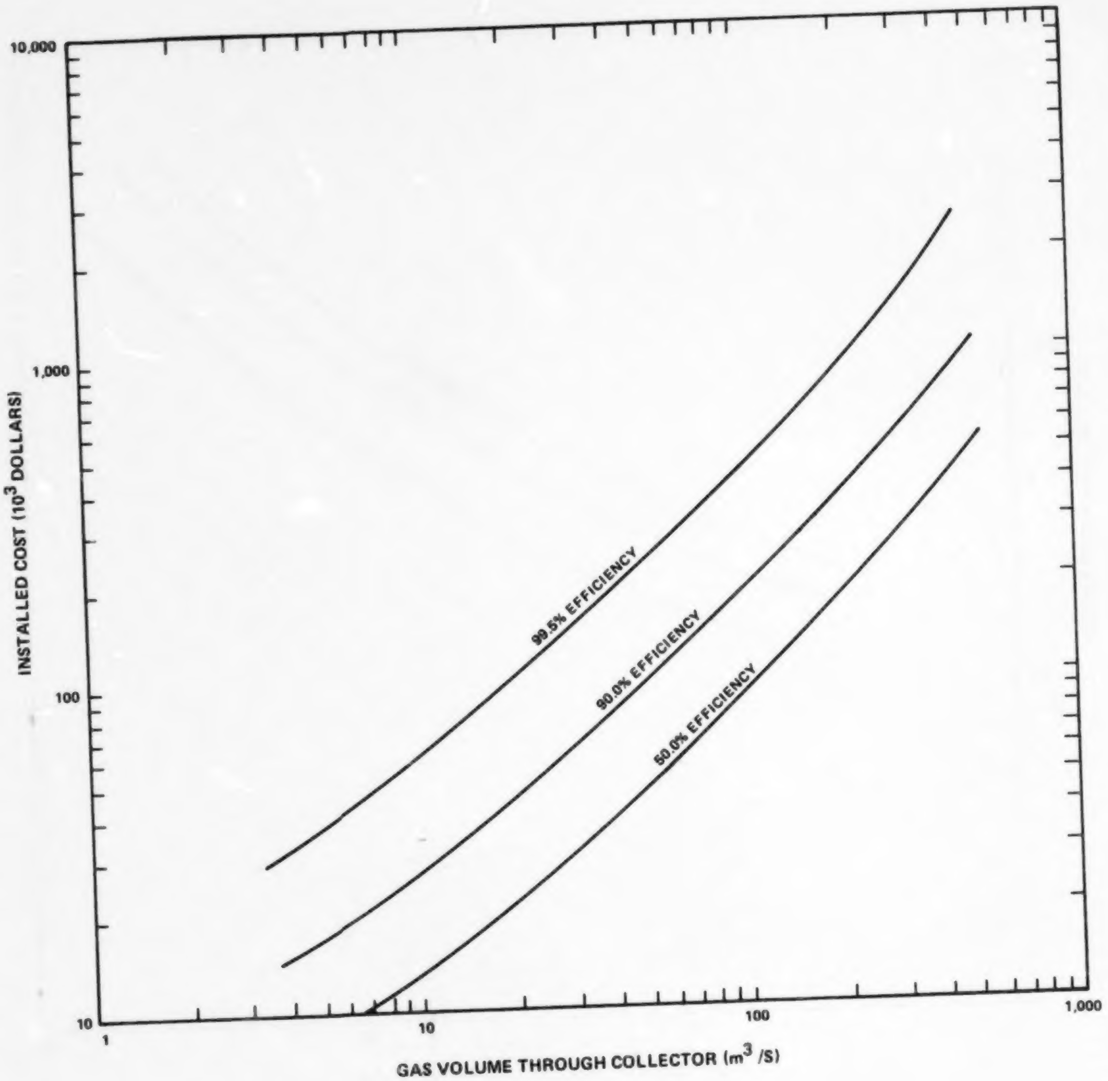

Figure D-15. Estimated installed cost of fabric filters (1976 dollars).

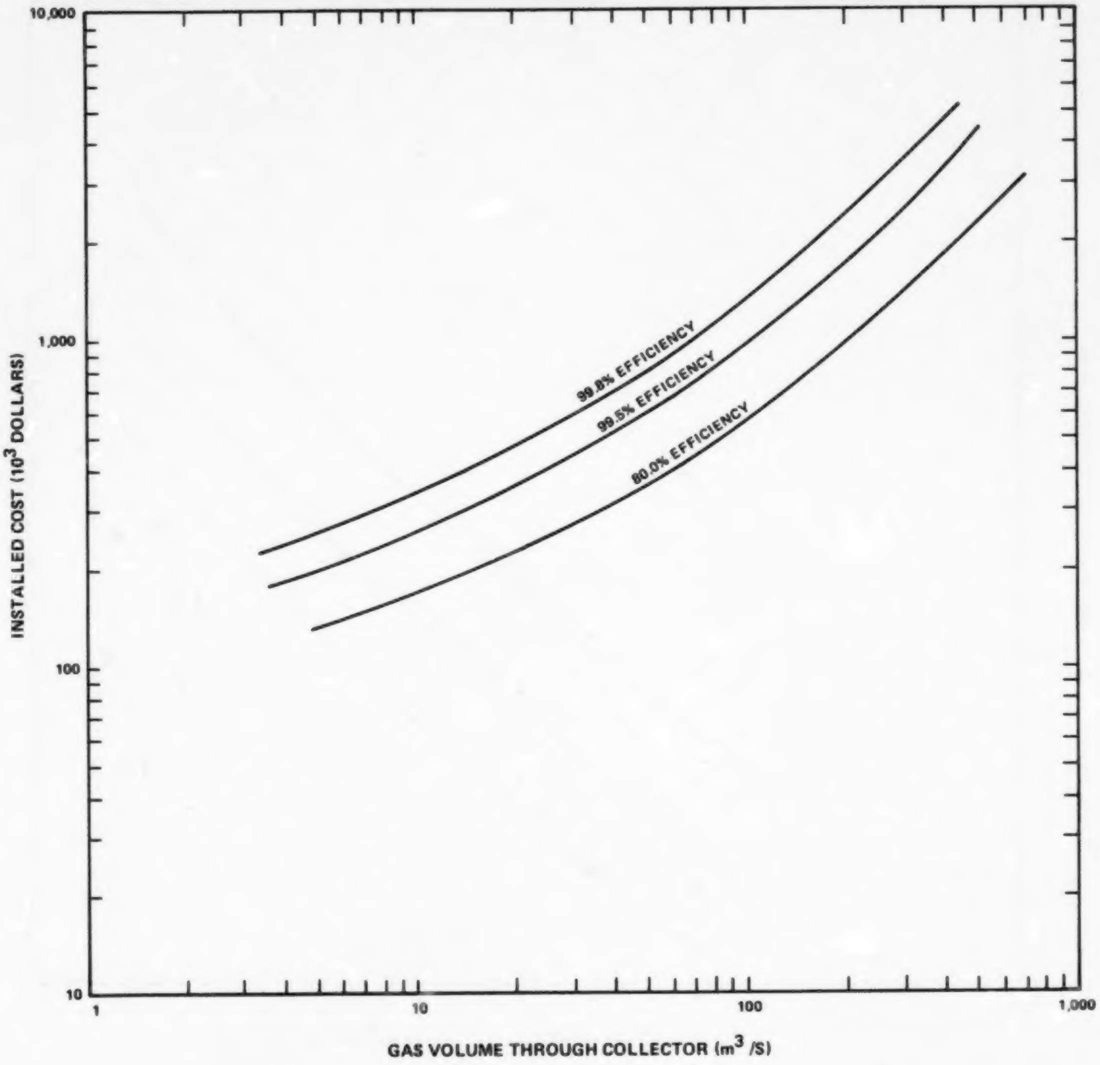

Figure D-16. Estimated installed cost of electrostatic precipitator (1976 dollars).

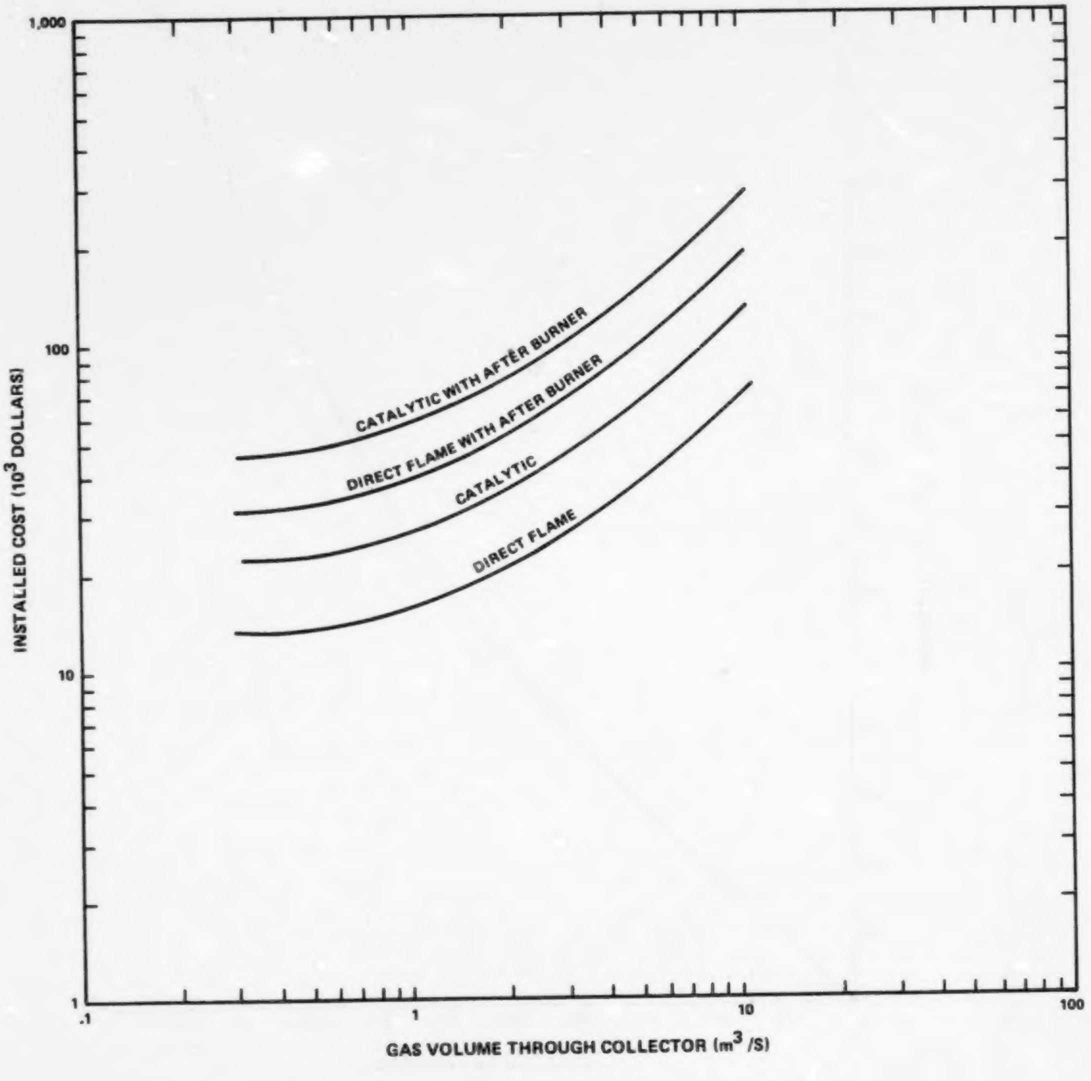

Figure D-17. Estimated installed cost of afterburners (1976 dollars).

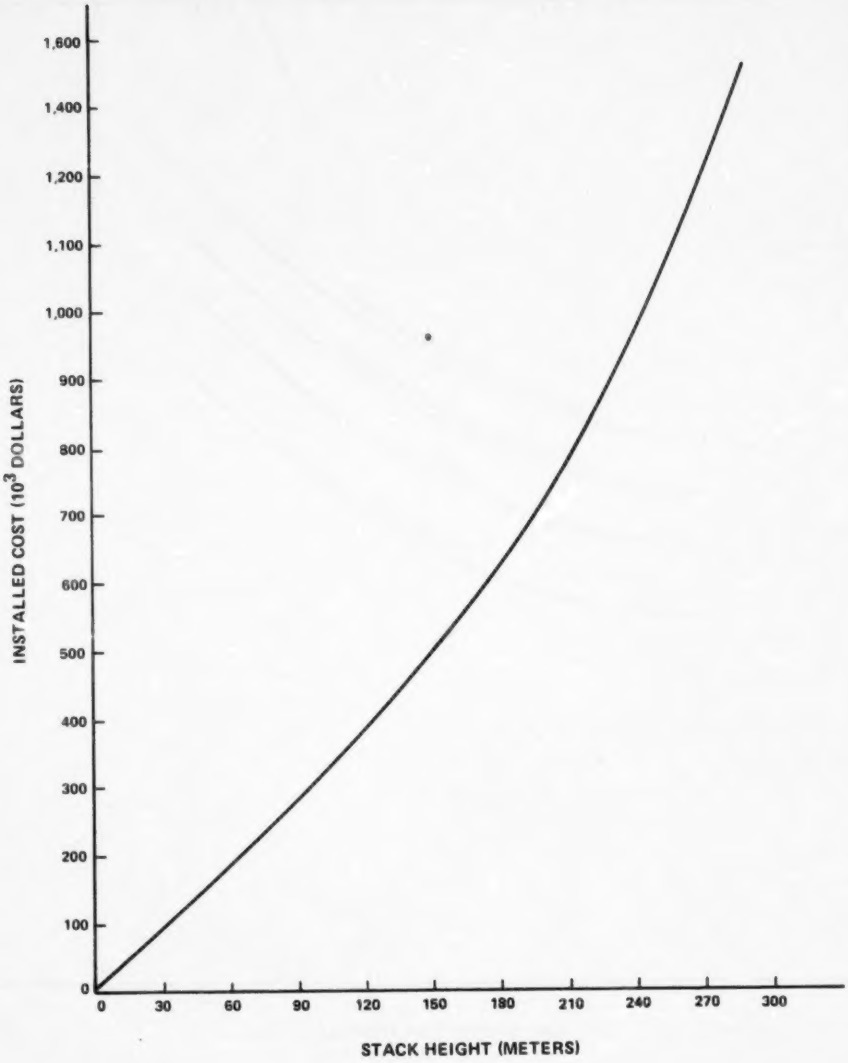

Figure D-18. Estimated installed cost of stacks (1976 dollars).

TABLE D-9. COMPONENTS OF CAPITAL COST (Ref. D-10)

Component	% of Capital Cost
Major control equipment	35%
Auxiliary or accessory equipment	15%
Field installation equipment	20%
Project management and engineering	17%
Indirect costs (freight, taxes, contractor overhead, contractor profit)	13%
	100%

TABLE D-10. TOTAL INSTALLATION COST FOR VARIOUS TYPES OF CONTROL DEVICES EXPRESSED AS A PERCENTAGE OF PURCHASE COSTS (Ref. D-4, D-10)

Equipment Type	Cost, percent			
	Low	Typical	High	Extreme High
Gravitational	33	67	100	---
Dry centrifugal	35	50	100	400
Wet collector:				
Low, medium energy	50	100	200	400
High energy*	100	200	400	500
Electrostatic precipitators	40	70	100	400
Fabric filters	50	75	100	400
Afterburners	10	25	100	400

* High-energy wet collectors usually require more expensive fans and motors.

Operation and maintenance costs are frequently a substantial percentage of the total air pollution cost and are usually the most difficult to assess. The annual operating cost is defined to be the expenditure incurred in operating a control device at its designed collection efficiency for one year, while maintenance cost is the expenditure required to sustain the operation of a control device at its efficiency. Operating and maintenance costs per year (including maintenance) are shown in Figures D-19 through

D-23, for various pollution control devices. Annual operating and maintenance costs vary considerably and are dependent on volume of gas cleaned; pressure drop across the system; operating time; utility costs for electricity, fuel, water, and other raw materials; mechanical efficiencies of motors, fans, and pumps; and geographical location.

Annualized operating cost is the actual cost per year to operate air pollution control equipment and includes the depreciation of the capital investment over the expected life of the equipment, interest rate, and operation and maintenance costs.

A breakdown of typical annualized operating costs expressed as percent annual operating costs is shown in Table D-11. The annualized capital cost assumptions utilized to develop Figures D-24 through D-28 are:

1) Purchase and installation costs are depreciated over 20 years

2) Straight line method of depreciation (5.0 percent per year)

3) Interest rate of 8.5 percent of the capital investment.

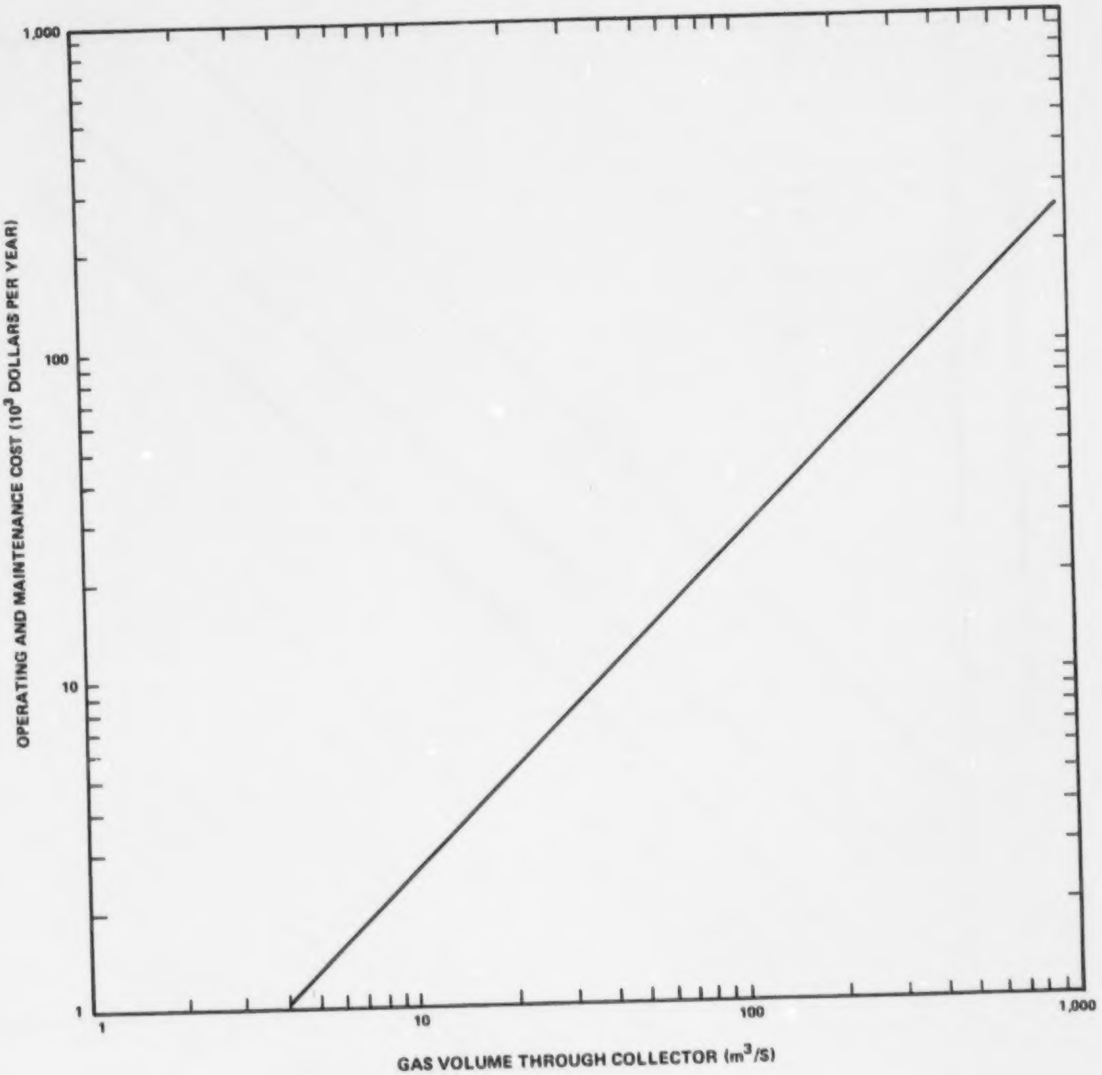

Figure D-19. Estimated operating and maintenance cost of mechanical collectors (1976 dollars).

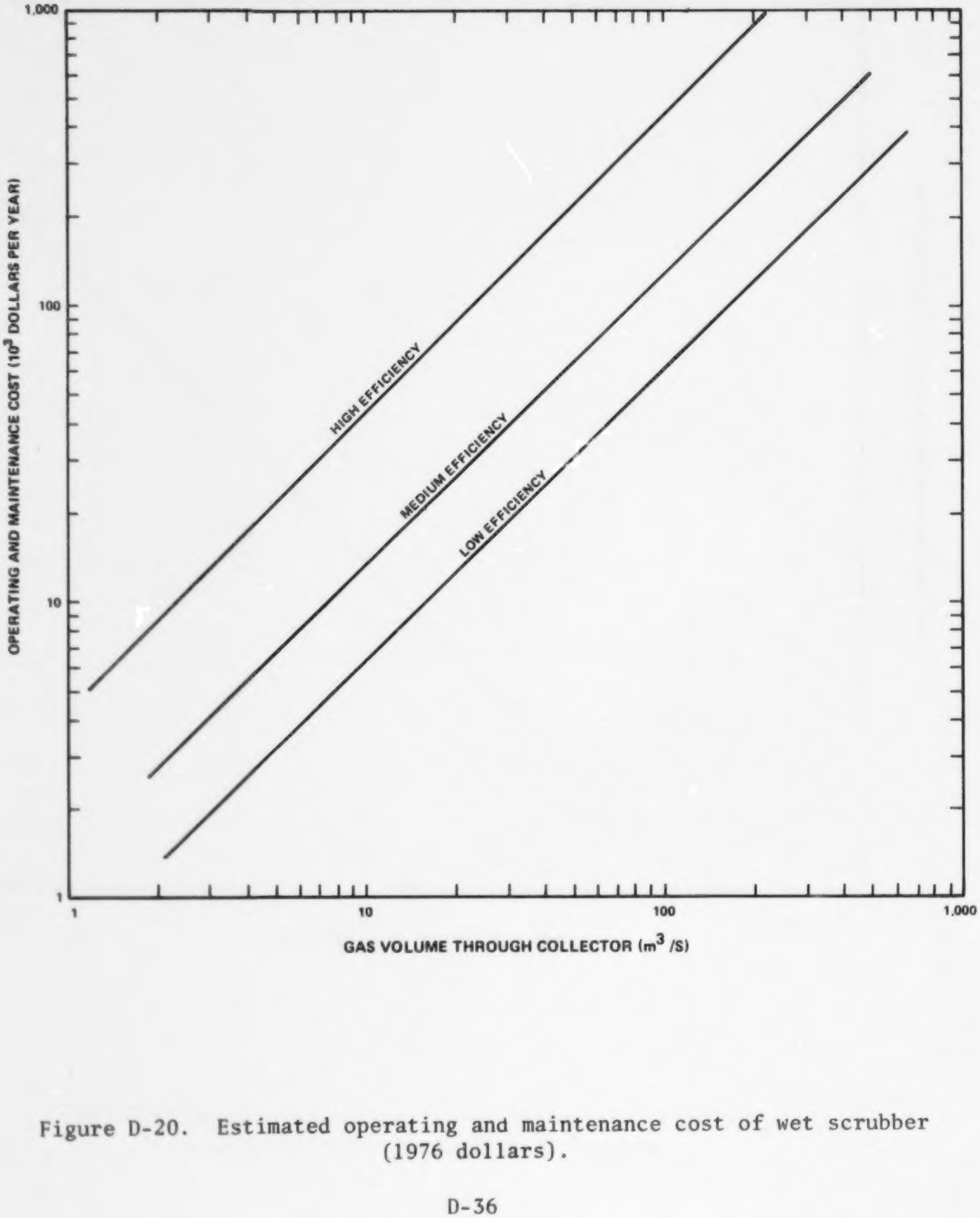

Figure D-20. Estimated operating and maintenance cost of wet scrubber (1976 dollars).

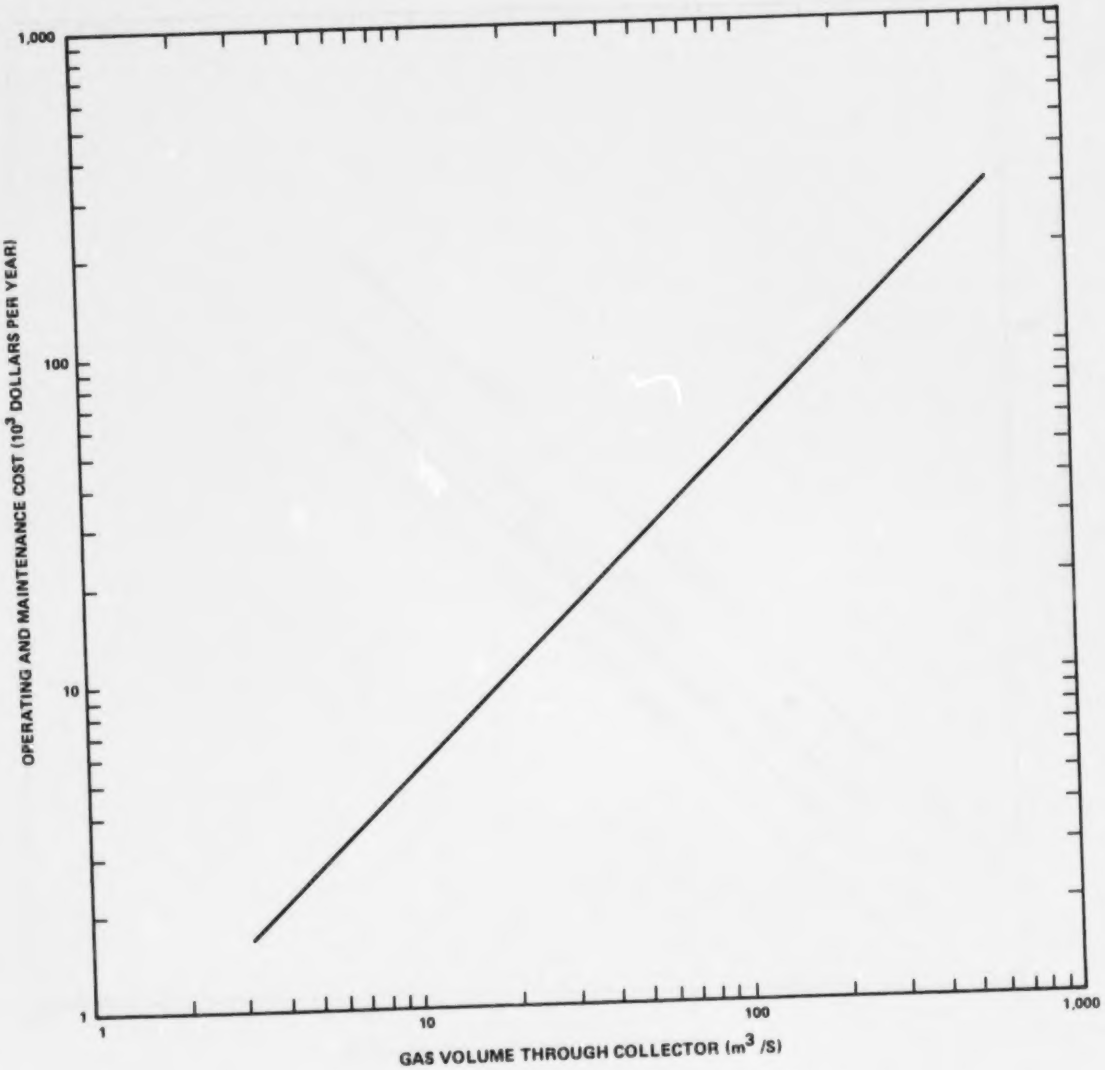

Figure D-21. Estimated operating and maintenance cost of fabric filters (1976 dollars).

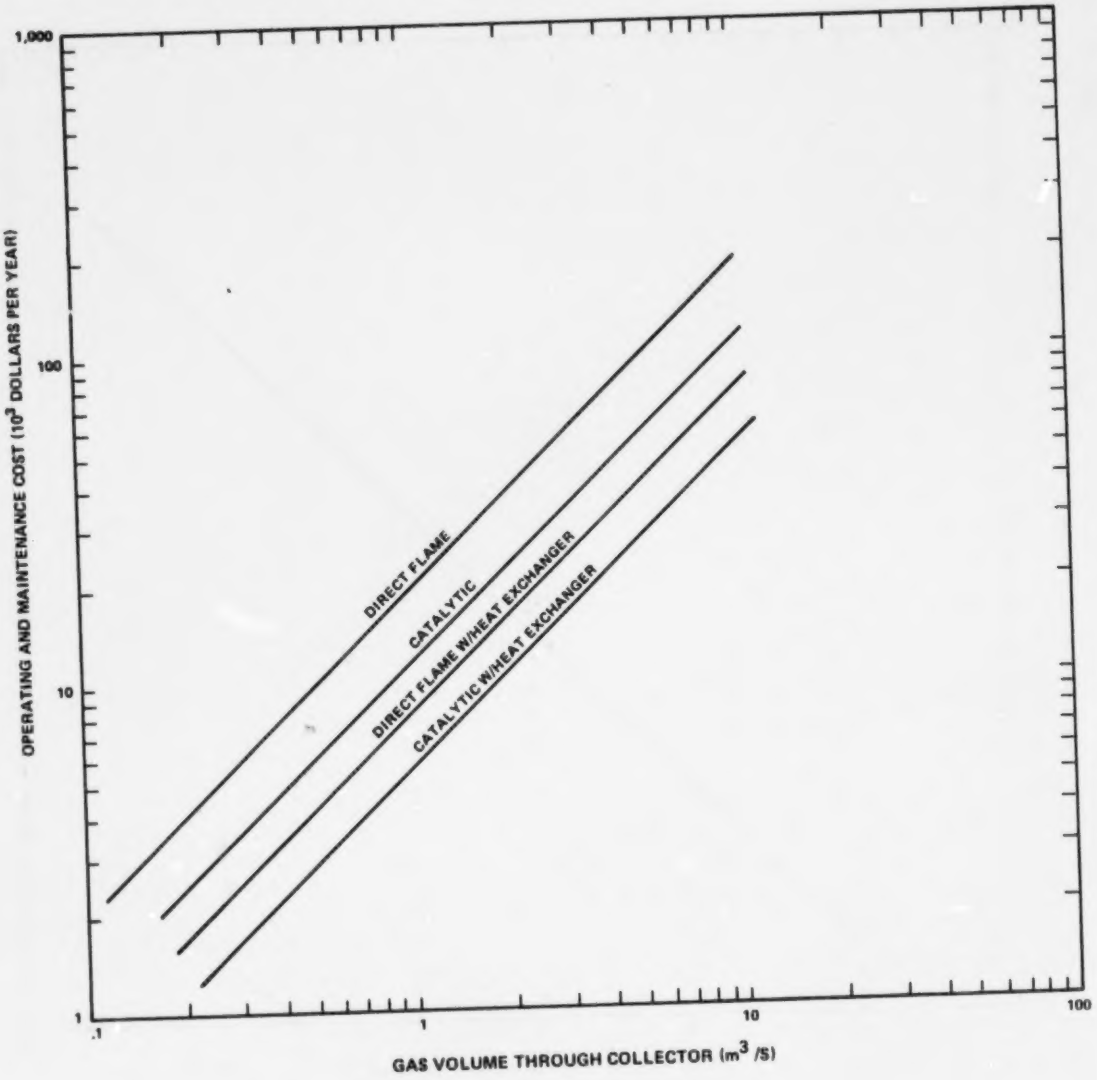

Figure D-22. Estimated operating and maintenance cost of afterburners (1976 dollars)

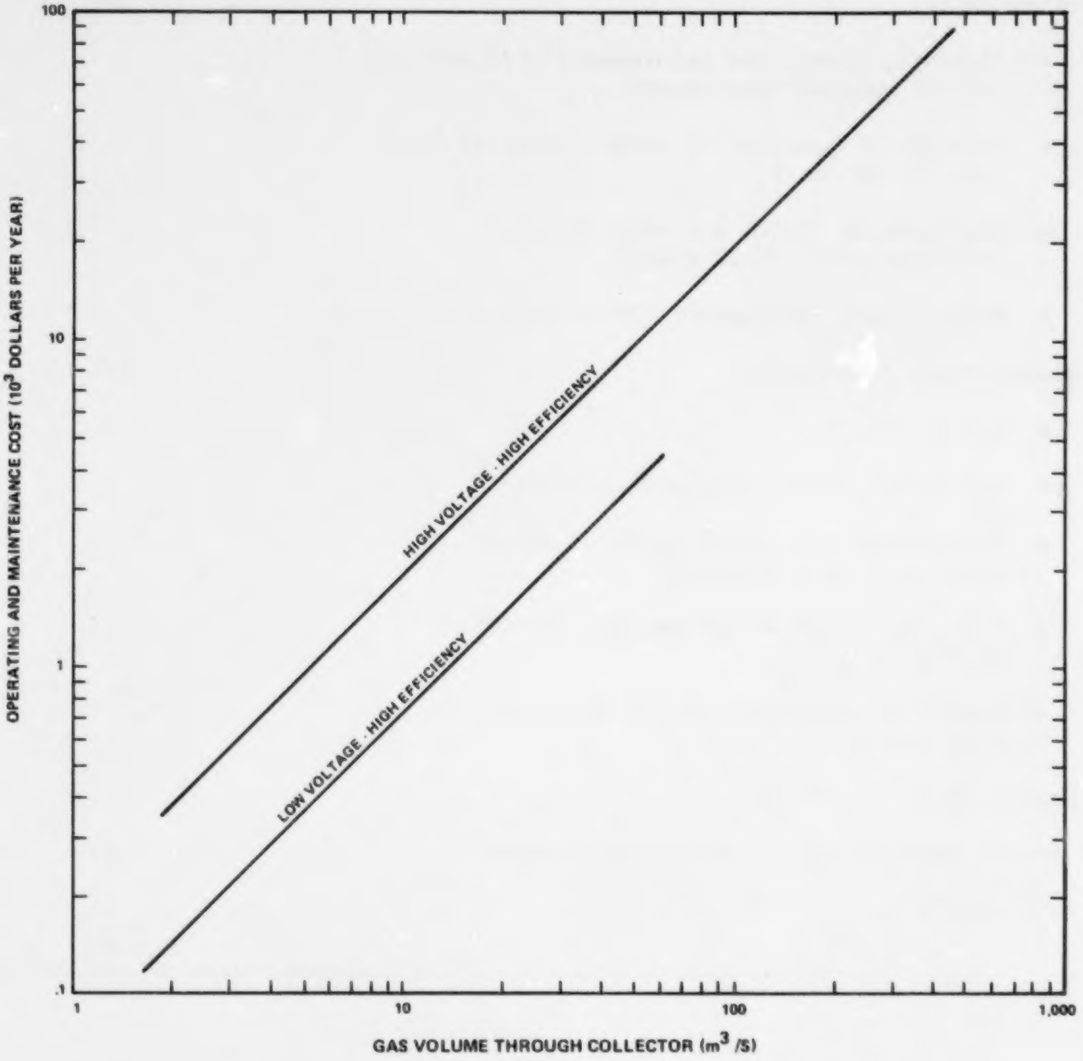

Figure D-23. Estimated operating and maintenance cost of electrostatic precipitator (1976 dollars)

TABLE D-11. TYPICAL ANNUALIZED OPERATING COST BREAKDOWN

Type	% of Total Annual Operating Cost
Fixed costs	20%
• Interest, taxes, and insurance (7-12% per year of capital investment)	
• Rent (8-10% per year of total installed cost, 15-20 years)	
• Depreciation (5-10% per year of total installed cost, 15-20 years)	
• Research and development (5% of sales)	
Direct Production Costs	60%
• Raw materials	
• Operating, supervising and clerical	
• Maintenance and repair (M/R) (2-10% of total capital investment)	
• Operating supplies and payroll (10-20% of M/R)	
• Power and utilities (10-20% of production costs)	
General Plant Overhead	10%
General Administration and office overhead	6%
Contingencies	4%
	100%

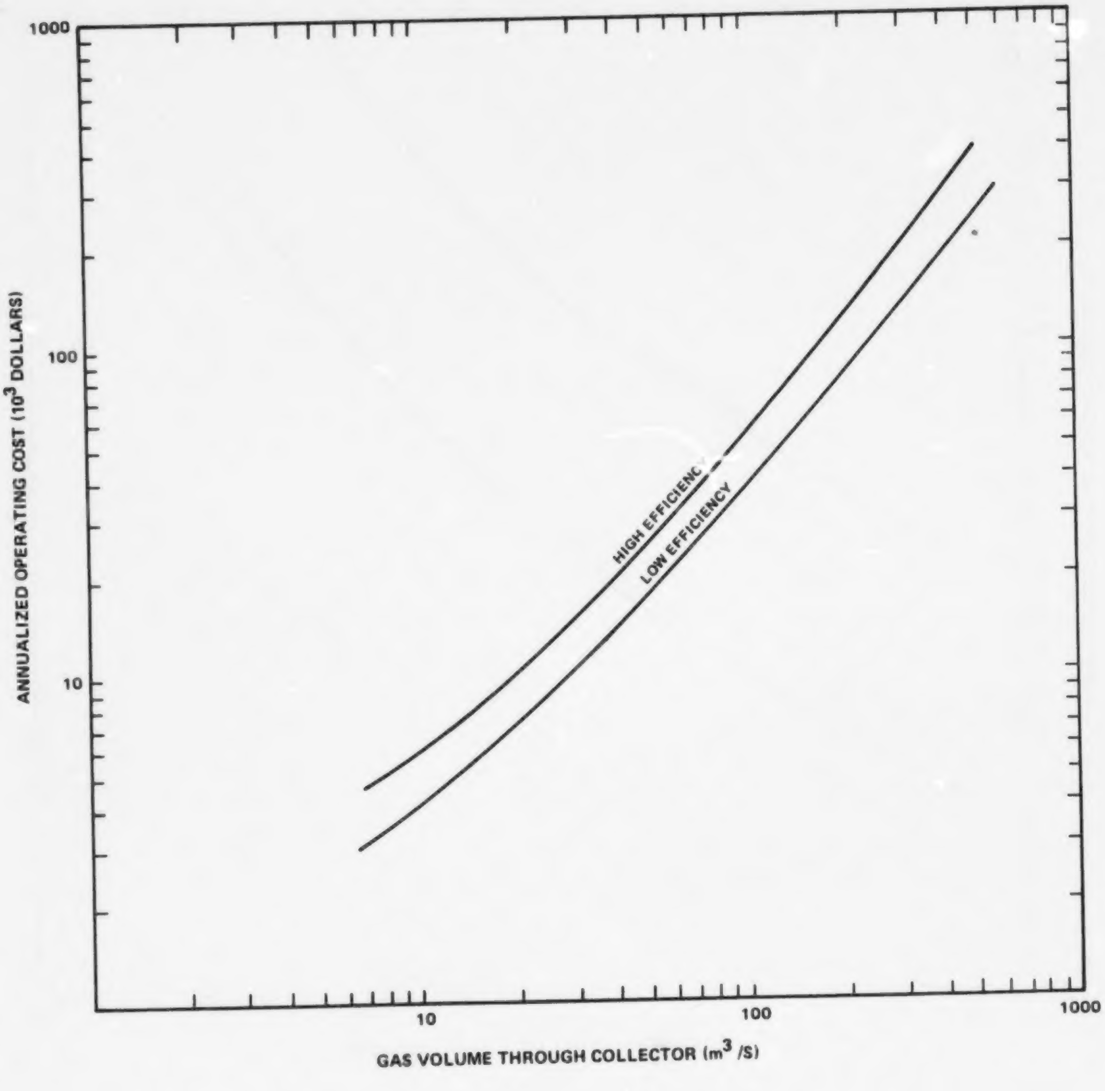

Figure D-24. Estimated annualized operating cost of mechanical collectors (1976 dollars).

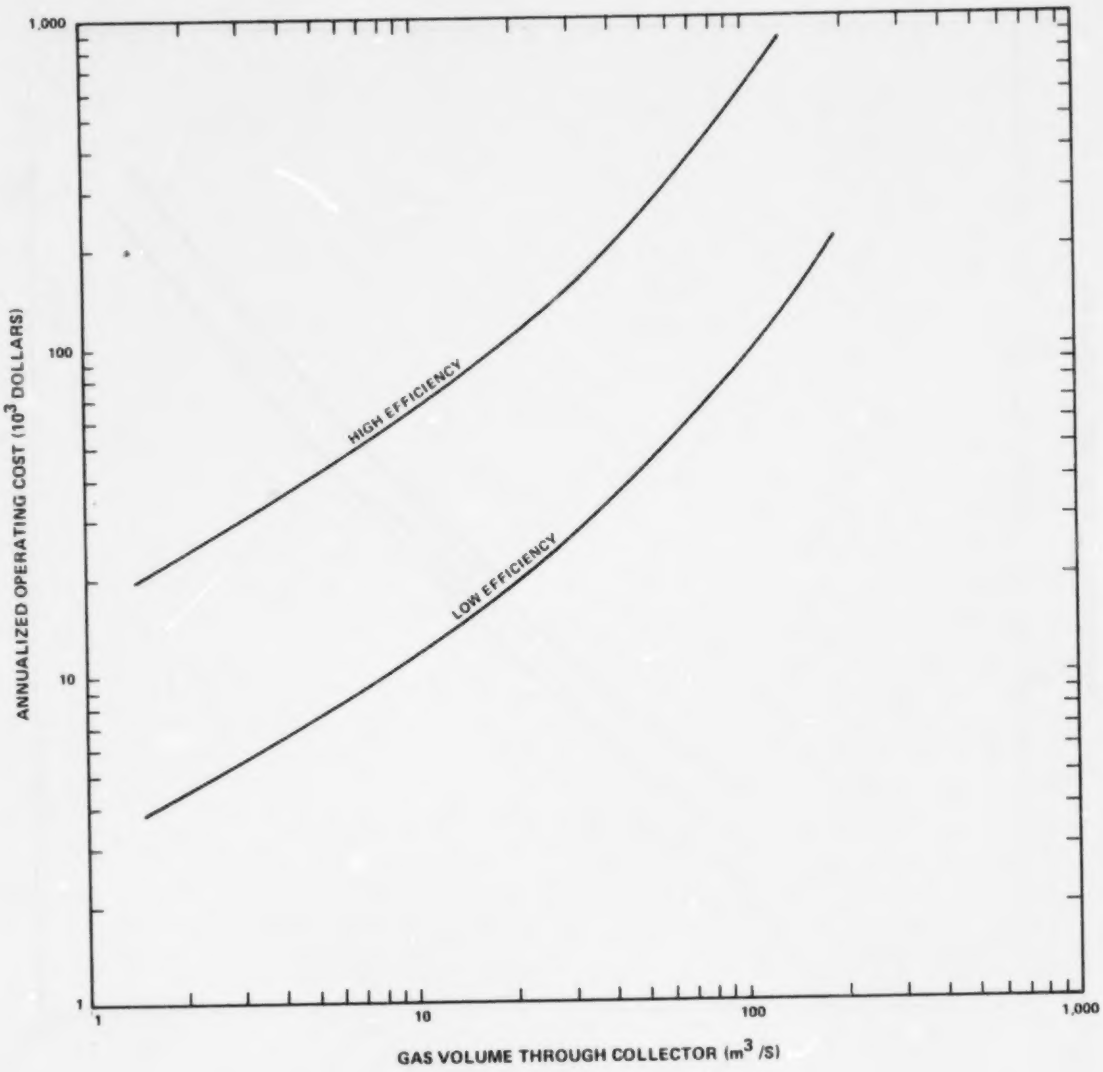

Figure D-25. Estimated annualized operating cost of wet scrubbers (1976 dollars).

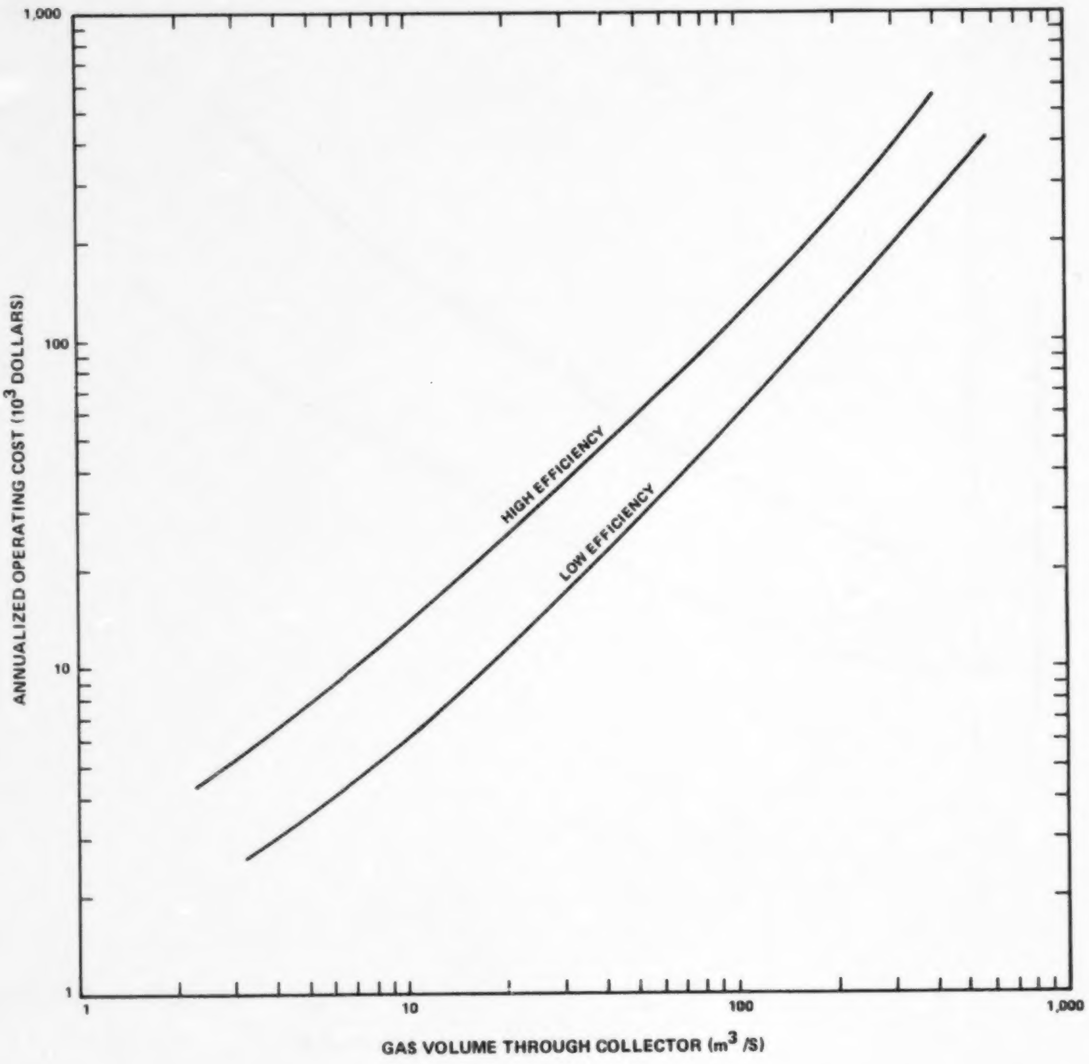

Figure D-26. Estimated annualized operating cost of fabric filters (1976 dollars).

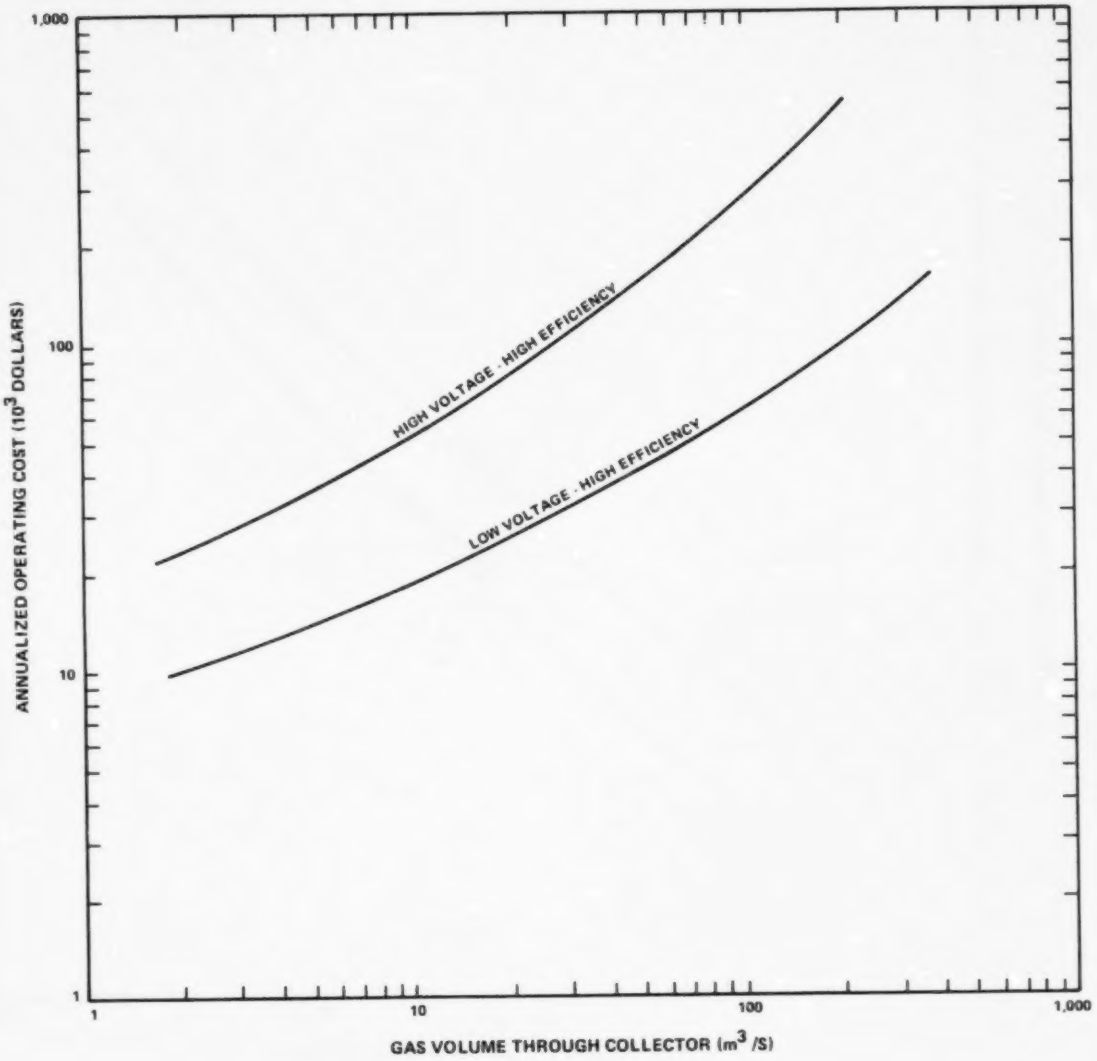

Figure D-27. Estimated annualized operating cost of electrostatic precipitator (1976 dollars).

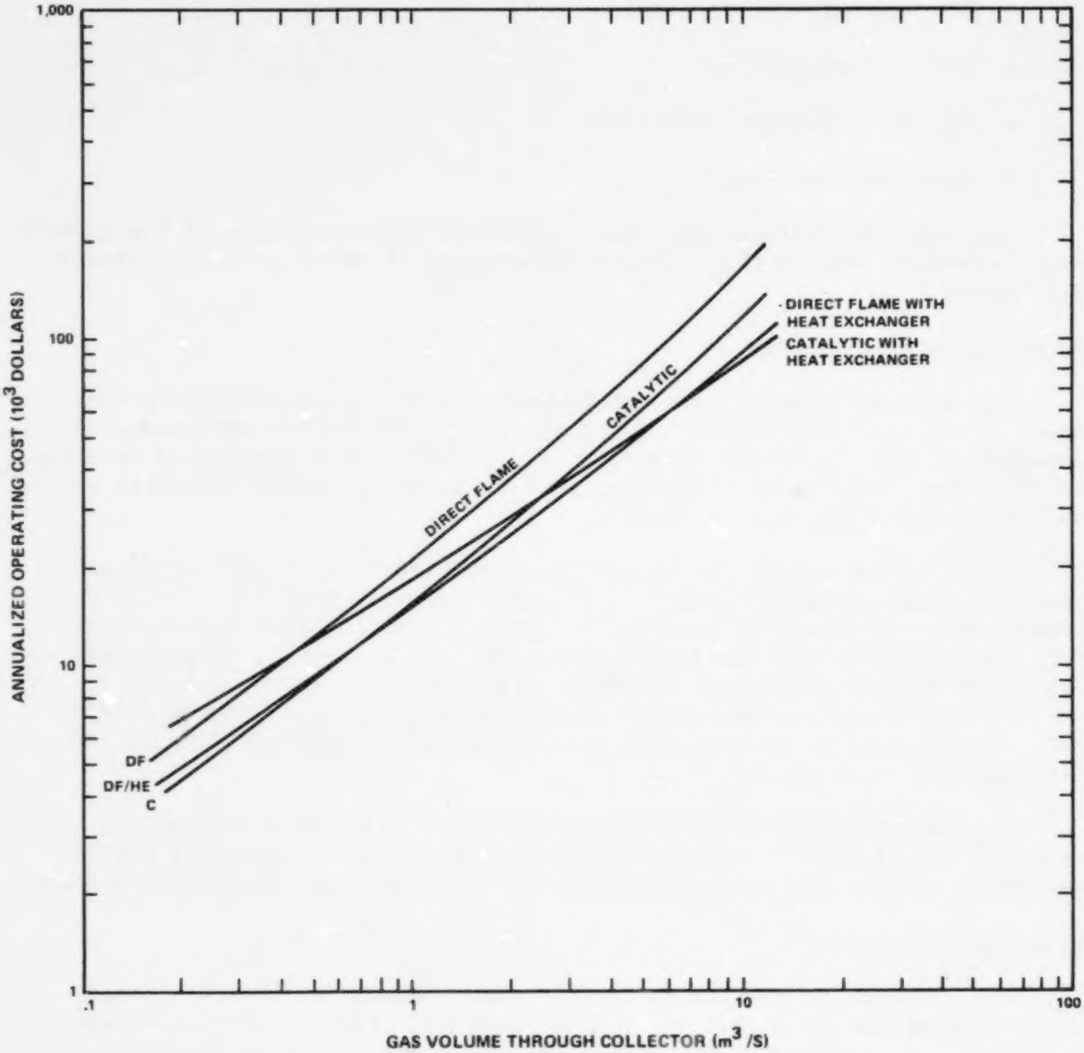

Figure D-28. Estimated annualized operating cost of afterburners (1976 dollars).

WATER POLLUTION

Introduction

A short discussion of the water pollution considerations pertaining to waste-to-energy conversion systems follows, that encompasses:

- The water pollution problem
- Effluent guidelines
- Typical treatment processes
- Cost considerations

More detailed information can be obtained by examination of the associated references and by consulting manufacturers of water pollution control equipment.

Water Pollution Problem

Contaminated waters can occur in waste-to-energy conversion systems from (1) the spentscrubber liquid of air pollution control equipment, (2) internal process clean-up systems, or (3) leachate from landfilled residues. In all three cases control measures must be taken to reduce the level of the contamination to acceptable levels.

These contaminants can include partially burnt and oxidized material from the spent scrubber liquid; slag, char, and oils from the various processes of waste-to-energy conversion systems; and heat from quench water. More specifically, the wastewater contamination can consist of suspended and dissolved solids, chlorides, sulfates, phosphates, hardness, alkalinity, and pH. In many cases the wastewater discharges will exert an oxygen demand, both chemical oxygen demand (COD) and biological oxygen demand (BOD) and may also contain heavy metals.*

Once a conversion system has been analyzed as to what the wastewater characteristics will probably consist of, the process of choosing control equipment to meet effluent guidelines and water quality standards can begin.

Effluent Guidelines

The issuance of permits to "point source" dischargers is the basic regulatory mechanism of water pollution control. These permits are issued, nationally, by either the Environmental Protection Agency or the state in which the source is located. Local permits are also a usual requirement for industrial wastewater dischargers.

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* For the seven candidate systems chosen for analysis, the wastewater characteristics are discussed, where known, and the reader is referred to them for more specific details.

Effluent guidelines and water quality standards are not available for all industries, with waste-to-energy systems being included in this category. When effluent guidelines have not been published, permits for industrial dischargers are based on the best technical judgement of feasible control technology. Where water quality standards are not available, effluent guidelines with maximum daily pollutant loads are the basis for the permit. (Ref. D-11) Section 301, part (2) (A) of the Federal Water Pollution Control Act states:

> "...not later than July 1, 1983, effluent limitations for categories and classes of point sources, other than publicly owned treatment works, which (i) shall require application of the best available technology economically achievable for such category or class, which will result in reasonable further progress toward the national goal of eliminating the discharge of all pollutants, as determined in accordance with regulations issued by the Adminstrator pursuant to section 304 (b) (2) of this Act, which such effluent limitations shall require the elimination of discharges of all pollutants if the Adminstrator finds, on the basis of information available to him (including information developed pursuant to section 315), that such elimination is technologically and economically achievable for a category or class of point sources as determined in accordance with regulations issued by the Administrator pursuant to section 304(b)(2) of this Act, or (ii) in the case of the introduction of pollutant into a publicly owned treatment works which meets the requirements of subparagraph (b) of this paragraph, shall require compliance with any applicable pre-treatment requirements and any other requirement under section 307 of this Act;..." (Ref. D-12)

Once effluent guidelines and/or water quality standards are known, the process of choosing a wastewater treatment system to meet them can continue, with the next step being to identify some possible methods of control.

Typical Treatment Processes

Contaminants in waste water are removed by physical, chemical, and biological means. Treatment in which the application of physical forces predominates are called unit operations. Sedimentation is an example of this type of treatment. Treatment methods in which the removal of contaminants is accomplished by the addition of of chemicals or by biological activity are called unit processes. Precipitation is an example of a chemical unit process and biological oxidation is an example of a biological unit process.

Activated Sludge--

In the activated sludge process, the waste is stabilized biologically in some type of holding vessel under aerobic conditions. Diffused or mechanical aeration is used to achieve this aerobic environment. After the waste is treated in the holding vessel, the resulting biological material is separated from the liquid in a settling tank. This type of biological oxidation of wastewater has proven to be one of the most effective methods for the treatment of both municipal and organic industrial wastes. There are various modifications to the activated sludge process, descriptions of which can be found in the literature.

Wet Oxidation--

Wet oxidation is a physiochemical method for the treatment of waste water containing oxidizable impurities, consisting of flameless combustion at elevated temperatures of 150 - 350°C (300 - 650°F) and high pressures of 3.1 to 17.2MPa (450 - 2500 psig). Compressed air is fed into the pressure vessel as the source of oxygen for the reaction process, which consists of hydrolysis (solubilization of solids and breakdown of long-chain hydrocarbons), mass transfer (oxygen into solution), and chemical oxidation.

Carbon Absorption--

The absorption process consists of the collection of substances that are in solution on a suitable interface, typically activated carbon. The effluent is passed through a bed of activated carbon granules and up to 98% of the impurities are removed from the water by absorption when sufficient contact time is provided for this process. The carbon system usually consists of a number of columns of basins used as contactors and these are connected to a regeneration system. This process has become more attractive in recent years due to the development of economical regenerative methods.

Lagoons and Stabilization Ponds--

The two basic types of lagoons are 1) aerated and 2) aerobic-anaerobic. In an aerated lagoon, the essential function is waste conversion whereby the BOD content of the effluent is reduced with the contents of the lagoon being completely mixed and oxygenated by surface aerators or diffusers. Both the incoming solids and the biological solids do not settle out and therefore must be removed in a settling basin or tank before discharging the effluent. In the case of an aerobic-anaerobic lagoon, the contents are not completely mixed by the aerators and a significant portion of the incoming solids and waste conversion solids settle to the bottom of the lagoon, eventually producing an anaerobic condition at the bottom.

Stabilization ponds are bodies of water, relatively shallow, in which wastewater is treated. Stabilization ponds (or oxidation ponds) have a longer detention time than lagoons but are similar in principle. Classification is usually by type of biological activity: aerobic, aerobic-anaerobic, and anaerobic. An aerobic pond is especially suited to strong organic wastes and brings about rapid stabilization.

Other Methods--

Since the wastewater effluents from waste-to-energy systems are so diversified, some having high BOD and COD loadings, other chemical or physical procedures not usually considered in wastewater treatment could be attempted; examples are reduced pressure distillation, absorption on nonionic resins or molecular sieves, and liquid-liquid extraction, but further research is needed.

Leachate Control in Landfilling--

Leaching can be defined as "removal by the action of a percolating liquid." Leachate production in landfills is related to the amount of water moving through the landfill and is a potential chemical and biological pollutant of both ground and surface waters. The primary design limitation for leachate is that the landfill not hinder any current or projected use of the water resources in the area. Utilization of so-called Class I* disposal sites would afford excellent protection from leachate emanating from waste-to-energy conversion systems residue that is landfilled.

More detailed information on the abovementioned treatment processes and others can be found in the literature.

Cost Considerations

The cost of treating wastewaters from waste-to-energy conversion system is difficult to assess due to the many available treatment processes and the widely varied quantities and qualities of the wastewater discharged. In general, highly mechanized systems tend to have low annual operational costs, but high initial costs. Conversely, less sophisticated systems might be built at lower initial costs, but have higher annual operational costs. Once installed, facilities can incur annual costs over a 20 year period amounting to five times the initial cost of the facilities.

The use of municipal facilities by industry is subject to the 1972 Amendments to the Federal Water Pollution Control Act which identify such specific requirements for public treatment of industrial waste as:

- Industrial plants discharging pollutants not susceptible to treatment by the municipal plants will be required to pretreat their discharges.
- The costs of providing additional plant capacity for treating industrial wastes are not eligible for Federal grant funding.
- Industries must pay fairly for treatment services rendered, including the costs of interceptor and collector services (Ref. D-14).

In general, construction costs for industrial wastewater facilities can be grossly estimated by assuming approximately \$30-35/m^3-d treated (Ref. D-15).

ACOUSTIC CONSIDERATIONS

There are two primary considerations in dealing with noise for any facility. They are employee noise exposure, and the impact that the additional noise caused directly or indirectly by the facility will have upon the community at large.

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* Sites located on nonwater-bearing rocks or underlain by isolated bodies of unusable ground water, which are protected from surface runoff and where surface drainage can be restricted to the site or discharged to a suitable wasteway, and where safe limitations exist with respect to the potential radius of percolation. (Ref. D-13)

Employee noise exposure is regulated by the Department of Labor Occupational Noise Exposure Standard (OSHA). The Code of this federal regulation is: Title 29, Chapter XVII, Part 1910, Subpart G, 36FR 10466, May 29, 1971. The basic constraints dictated by this standard are as follows:

Permissible Noise Exposure

Duration per Day, Hours	Sound Level, dBA* Slow Response
8	90
6	92
4	95
3	97
2	100
1-1/2	102
1	105
1/2	110
1/4 or less	115

* dBA is the abbreviation for the sound energy level in decibels as measured by the A-weighted network of a sound meter; this scale approximates the weighted response of a normal human ear.

When the daily noise exposure is composed of two or more periods of noise exposure, of different levels, the combined effect should be considered, rather than the individual effects of each. If the sum of the following exceeds unity, then, the mixed exposure should be considered to exceed the permissible limit.

$$\frac{C_1}{T_1} + \frac{C_2}{T_2} + \frac{C_n}{T_n} \leq 1$$

Where: C_n = The total time of exposure at a specific noise level.

T_n = The total time of exposure permitted at that level.

Exposure to impulse or impact noise should not exceed 140 dBA peak sound pressure level.

Community noise levels are typically regulated by state and local agencies, with standards varying from area to area. They also depend on the location of the proposed facility with regard to zoning restrictions and the proximity of residential areas.

There are several potential noise problem areas in waste processing facilities. Some major equipment-related noise sources are: delivery vehicles, waste moving vehicles, screens, compressors, compactors, shredders, fans, pumps, furnaces, cooling towers, conveyors, and atmospheric vents. Other less tangible sources are dumping and receiving bins, sorting bins, and other areas in which there exist impulse noises from metal to metal, rock to metal, or solid to metal contact.

Vehicular noise can be reduced by using rubber-tired tractors equipped with mufflers on their exhaust systems. Noise can be reduced by buying quieter equipment initially and by acoustically treating existing noisy equipment by enclosures or lagging. Impulse noise can be reduced by applying rubber or plastic lining to bins, truck beds, and like surface areas. Combustion roar from furnaces can be reduced through the addition of acoustic plenums for combustion air intakes. Noise caused by atmospheric vents can be reduced by fitting the vents with diffusers or silencers.

Finally, noise areas in the facility can be posted for limited access and thus, by administrative control, the employer can insure that an employee is not exposed to excessively loud noises that will present a hearing damage risk.

If the noise level at the plant boundary still exceeds local ordinances after initial design and equipment selection efforts, further more refined scrutiny of noise sources within the facility and further acoustic treatment would be required. This could be a very costly endeavor and consequently maximum attention should be employed in site selection and facility design to insure compliance with all noise regulations prior to construction.

The increase of vehicular traffic on residential surface streets must also be considered. If there will be an increase of traffic, the annoyance to the community may be significant. When it is necessary to traverse residential areas, several approach routes to the facility should be employed, reducing the impact on any one section of the community. The use of residential surface streets should be avoided whenever possible because of the usually very stringent regulations imposed in such areas. These regulations are stated in terms of L_{dn}, the day-night level of the average A-weighted noise level integrated over a 24-hour period. A 10 dB penalty is assessed from the hours of 10:00 p.m. to 7:00 a.m. If a local ordinance states that the maximum permissible L_{dn} is 55, a facility may not emit more than an average of 55 dBA from 7:00 a.m. to 10:00 p.m., and an average of 45 dBA from 10:00 p.m. to 7:00 a.m.; furthermore, a maximum allowable sound level is usually imposed.

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APPENDIX E

SI UNITS OF MEASUREMENT

"SI" is the offical abbreviation, in all languages, for the International System of Units (le Systême International d'Unités). It is an improved, coherent version of the metric system and has been recognized as the basic system of measurement by virtually all nations since its adoption in 1960. The International System has seven basic units from which most of the others can be derived:

Quantity	Unit	Symbol	To convert from	to	Multiply by[x]
Length	metre	m	foot	metre	3.048 000*E-01
Time	second	s			
Mass	kilogram	kg	pound	kilogram	4.535 924 E-01
Amount of substance	mole	mol			
Temperature	kelvin	°K			
Electric current	ampere	A			
Luminous intensity	candela	cd			

Two purely geometrical supplementary units are also used: The radian (rad) for measuring plane angles, and the steradian (sr) for measuring solid angles.

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[x] This system of mathematical notation is that basically adopted for computer operations. An asterisk following the conversion factor indicates an exact relation, i.e. all numbers to follow are zeros. All factors are written as a number greater than one and less than ten, and are followed by the letter E (for exponent), a plus or minus symbol, and two digits that indicate the power of ten by which the number must be multiplied to obtain the correct value. For example 3.523 907 E-02 is 0.035 239 07 while 3.386 389 E+03 is 3 386.389.

Derived units are expressed as algebraic combinations of the basic and supplementary units, and may have special names. Some important derived units are:

Quantity	Unit	Symbol	To convert from	to	Multiply by
Force	newton	$N = kg\cdot m/s^2$	pound-force	newton	4.448 222 E+00
Energy	joule	$J = N\cdot m$	Btu (International)	joule	1.055 056 E+03
Power	watt	$W = J/s$	hp (electric)	watt	7.460 000*E+02
Pressure	pascal	$Pa = N/m^2$	psi	pascal	6.894 757 E+03
Heating value	joule/ kilogram	J/kg	Btu/lb	MJ/kg	2.326 000*E-03

There are a number of other units which are not part of the SI but are nevertheless important and widely used, and therefore considered to be allowable units. Examples are the minute (min.), hour (h), day (d), and year (y) as measures of time; degrees (°), minutes ('), and seconds (") as measures of angles; and degrees Celsius (°C) for temperatures. Trivial names that formed a part of the old metric system should be avoided. Principal among these are the litre (which to be consistent with other volumetric units should be called a cubic decimetre, dm^3): the metric tonne, which is properly referred to as a megagram (Mg) throughout this report; and the micron, correctly now a micrometre, μm.

Two important conventions are used in the International System:

- Groups of three digits are separated by a space instead of a comma, although with four digits the spacing is optional
- Decimal multiples and submultiples of SI units are indicated by appropriate letter prefixes, although in certain instances scientific notation may be used:

Scientific Notation	Prefix	Symbol	Scientific Notation	Prefix	Symbol
10^{15}	peta	P	10^{-3}	milli	m
10^{12}	tera	T	10^{-6}	micro	μ
10^{9}	giga	G	10^{-9}	nano	n
10^{6}	mega	M	10^{-12}	pico	p
10^{3}	kilo	k	10^{-15}	femto	f

Conversions from U.S. customary units to SI must be carried to a sufficient number of digits to keep the accuracy of the original quantity. In dealing with nominal values, such as "2-inch" pipe, exact conversions are used to avoid ambiguities.

The authority followed here for application of SI is American National Standard Z 210.1, available through the American Society for Testing and Materials as ASTM E380-76, "Standard for Metric Practice," approved January 19, 1976. An additional guide to the system is "Conversion of Operation and Process Measurement Units to the Metric (SI) System," American Petroleum Institute Publication 2564, March 1974.

Other conversions used within the report are as follows:

To convert from	to	Multiply by
acre	m^2	4.046 873 E+03
atmosphere, standard	Pa	1.013 250*E+05
barrel, 42-gal	m^3	1.589 873*E-01
Btu/ft^3	MJ/m^3	3.725 895 E-02
Btu/SCF (60°F, 1 atm)	MJ/Nm^3 (0°C, 1 atm)	3.938 080 E-02
ft^2	m^2	9.290 304*E-02
ft^3	m^3	2.831 685 E-02
ft^3 (standard)	m^3 (normal)	2.679 102 E-02
ft^3/min	m^3/s	4.719 474 E-04
gallon, U.S.	m^3	3.785 412 E-03
gallon, U.S./min.	m^3/s	6.309 020 E-05
grain/SCF	g/Nm^3	2.418 680 E+00
kcal, International	J	4.186 800*E+03
lb/ft^3	kg/m^3	1.601 846 E+01
lb/gal U.S.	kg/m^3	1.198 264 E+02
mile	km	1.609 347 E+00
ton, short	Mg	9.071 847 E-01